Bridging Law and Soil Science to Promote Soil Health

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OPINION

Bridging Law and Soil Science to Promote Soil Health

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ABSTRACT

Despite their crucial importance, soils generally enjoy limited legal protection, particularly when compared to other environmental domains such as air and water. We argue that legal systems are presently poorly equipped to effectively protect soil health, with a strong mismatch between the nature of law on the one hand, and the nature of soil on the other. Using the EU's proposed Soil Monitoring and Resilience Directive as an example, we bring together knowledge from a wide range of disciplines to outline key challenges for enhancing legal protection for soils. In brief, while laws require uniformity and legal certainty, soils are by nature heterogeneous and their functioning is still not completely understood. Furthermore, while legal systems are inclined to impact soils at the property scale and as a commodity, from a scientific perspective soils are highly spatially interconnected and a non-renewable resource. Finally, laws require mechanisms to detect (non-) compliance, which can be very costly and complex given the nature of soils. For each challenge we discuss opportunities for scientists and law- and policymakers to address these gaps, including in terms of improved communication and priority areas for further research. Although challenges remain, tools are available to enhance evidence-based soil management and strengthen soil protection efforts globally.

1 | Introduction

Achieving healthy soils that produce sufficient food has been an existential challenge for human civilizations since the advent of agrarian societies. In recent decades, awareness has grown that soils are a non-renewable resource and far more than a mere foundation for agriculture—they are also critical for carbon storage, biodiversity conservation, and water

Edwin Alblas, Anna Edlinger, and Julian Helfenstein contributed equally.

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Summary

- Legal systems are presently poorly equipped to effectively protect soil health.
- Laws treat soil as a commodity, ignoring its spatial interconnectivity.
- The proposed EU Soil Monitoring Directive can help bridge scientific uncertainty and legal standards.
- Strengthening science–law collaboration is needed to improve soil protection.

regulation—placing soil protection and restoration at the center of many environmental challenges (Lal et al. 2021). However, healthy soils are rapidly declining worldwide; in the European Union (EU) 60%–70% of soils are estimated to be unhealthy (Panagos et al. 2024), due to threats such as pollution, erosion, land take, and compaction. Despite their crucial importance, soil lacks comprehensive legal protection in the EU, which is all the more striking considering the ambitious legal protection that exists for environmental domains such as air and water (Heuser 2022). More fundamentally, we argue that legal systems are presently poorly equipped to effectively protect soil health, with a strong mismatch between the nature of law on the one hand, and the nature of soil on the other. While law can act as a powerful instrument to bring about sustainability transformations (Ebbesson 2010; Soininen et al. 2021), in order to effectively protect and restore soil health, there is an urgent need to find new ways to bridge the two different worlds of law and soil.

2 | The EU's Proposed Soil Monitoring and Resilience Directive

We illustrate our argument and propose solution pathways using the EU's proposal for a Soil Monitoring and Resilience Directive (hereafter "EU Soil Monitoring Directive," or simply "Directive") (European Commission 2023) as case study. Introduced by the European Commission in July 2023, this Directive arguably presents the most ambitious attempt to date to promote soil health beyond the individual country level. The proposal sets the "aspirational long-term objective" of achieving healthy soils by 2050 across Europe, and defines soil health as "the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services" (Directive, preamble par. 23; art. 3(4)). At the time of writing this article, the Directive is still going through the EU legislative process. On the 10th of April 2025, the European Parliament and the Council of the European Union reached, however, a provisional agreement during trilogue negotiations. While not all details of the final text have been disclosed, several central elements were confirmed, which were included in this article. The most recent version of the law is the Council version, published on June 17, 2024, which is the version referred to in this article. Following the provisional agreement, the Directive must undergo formal endorsement by both the European Parliament and the Council. A legal-linguistic review will then ensure consistency across all official EU languages. The Directive will then be formally adopted by the institutions and be published in the Official Journal of the EU. The Directive will enter into force 20 days after its publication, after which the Member States will have 3 years to transpose the Directive into national legislation. The Directive is structured around three pillars:

1. Soil Monitoring: The Directive primarily aims to harmonize soil health monitoring (systems) across Member States. It establishes a minimum common set of measurable soil health criteria, designed to "reflect and be based on the existing level of soil science" (Directive, preamble, par. 26).
2. Sustainable Soil Management: The second pillar tasks Member States with defining sustainable soil management practices guided by overarching EU principles. These practices are intended to be progressively implemented on managed soils.
3. Soil Contamination: The third pillar takes a risk-based, stepwise approach to managing contaminated sites. Member States are required to identify, investigate, and remediate contaminated areas to reduce risks to human health and the environment to "acceptable levels" (Directive, art. 12).

While the introduction of legal protection for soil is generally applauded (Köninger et al. 2022; van der Putten et al. 2023; Wadoux et al. 2024), the proposed Directive also raises important, challenging questions on how law can best address the inherent uncertainties and complexities of soil functioning. For instance: how can law's focus on uniformity and legal certainty best engage soil heterogeneity, interconnectedness, and scientific uncertainties?

Below, we flesh out these differences between law and soil and propose concrete ways forward for bridging them. In each section, we reflect on (1) how law works, (2) how soil works, (3) to what extent the EU Soil Monitoring Directive does (not) bridge these different worlds, and (4) possible ways forward. Our findings underscore priority areas for scientists and law and policymakers, both in terms of improved communication and knowledge gaps, to enhance evidence-based soil management and strengthen soil protection efforts globally.

3 | Uniform Laws Versus Heterogeneous Soils

A key foundation of legal systems is that they must provide general rules that apply uniformly across a given territory. For instance, road safety laws uniformly prohibit crossing a red traffic light and permit crossing when the light is green. Soils, by contrast, are complex, heterogeneous systems requiring more tailored, context-specific approaches (Figure 1A) (McBratney 1992). One farming practice may be destructive on one plot of land (red light needed) but could have minimal impact on another due to differences in soil composition and functioning (no red light needed). For instance, erosion risk varies considerably depending on factors such as soil texture, topography, and climatic conditions. While restrictions on certain land uses or tillage practices may be warranted on

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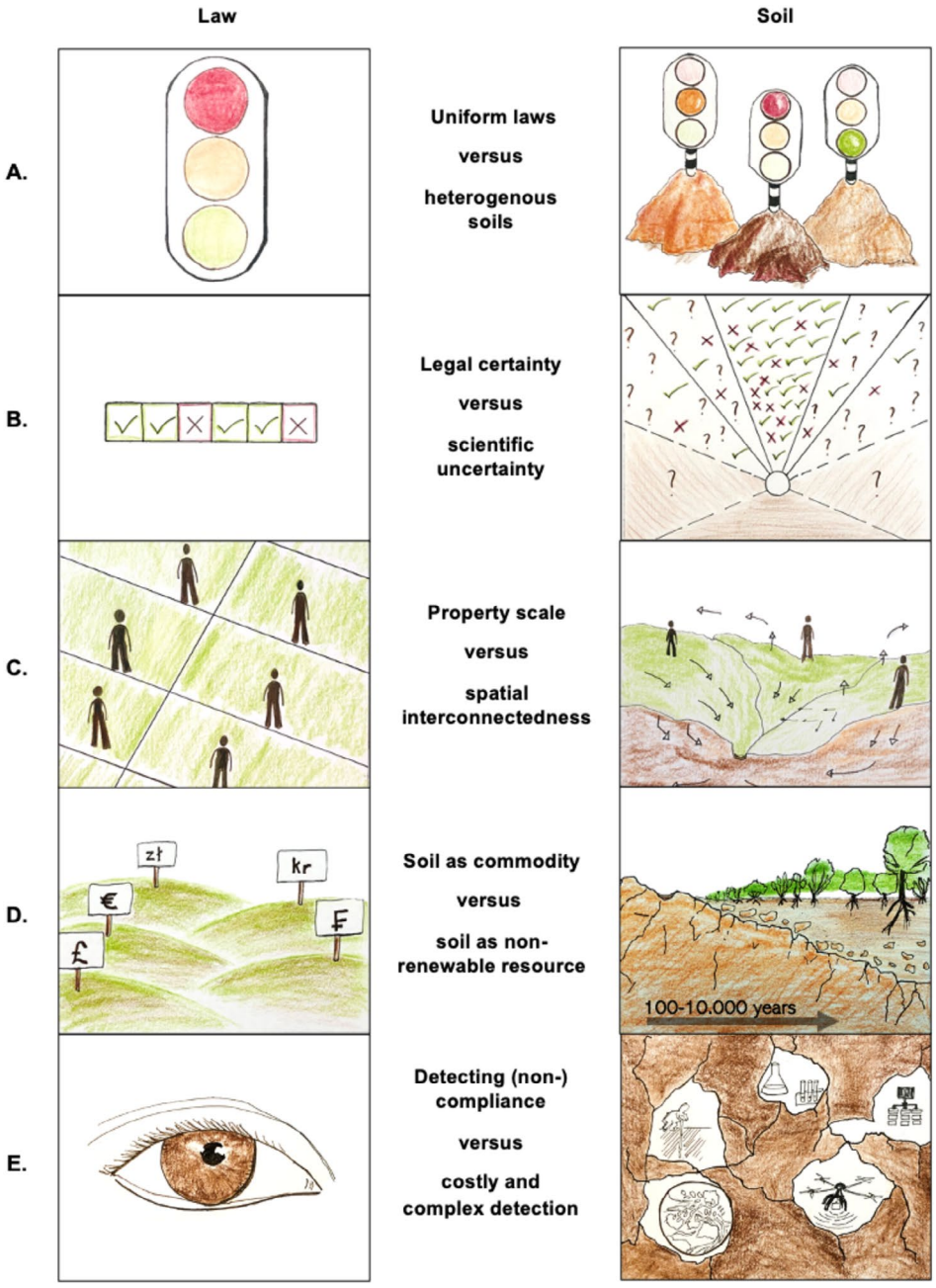

FIGURE 1 | Legal instruments to promote healthy soils require bridging fundamental differences between legal systems and soil functioning.

high-erosion-risk soils, a blanket prohibition across all soil types—including those with low erosion risk—could result in unnecessary trade-offs, particularly with regard to agricultural productivity and food security. Similarly, the capacity of soil to deliver ecosystem services and the societal demand for these services is fundamentally different based on soil type and land uses. These differences inherently call for context-dependent approaches when setting legal rules and regulations to protect soil health, including the need for defining context-specific evaluation criteria for what we consider a healthy state for soils.

Legal frameworks should accommodate such context-specificities. The proposed EU Soil Monitoring Directive addresses this in part by setting general, EU-level criteria for the healthy soil condition of so-called soil descriptors. For instance, one of the aspects of soil degradation is salinization, for which the soil descriptor "electrical conductivity" is used, as measured in deci-Siemens per meter. For salinization, the soil health criteria is set at <4 dS m^{-1}. Member States shall apply such criteria when monitoring soil health (Directive, art. 7). The soil health criteria thus represent the measurable value of an associated soil descriptor, of which parts are set at the EU level (Directive, Annex I, part A), and parts at the national level (Annex I, part B). Member States further have the discretion to establish context-specific target values for soil criteria, as well as "operational trigger values" indicating when interventions are required (Directive, art. 7(4)). These target values reflect the long-term aspirations of reaching healthy soils by 2050, but do not create a binding obligation

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for Member States to act. Operational trigger values, by contrast, reflect levels of soil degradation for which measures are required to improve soil health (Directive, art. 7(2); preamble, par. 27a). The trigger values are set by the Member States, to ensure that local conditions and practices, soil use, and current policies can be fully considered. However, this discretionary approach also has limitations, as it may result in high variations in monitoring practices across Member States that hinder comparability of soil health evaluations, while still failing to fully address small-scale soil variability effectively (Wadoux et al. 2024). To reconcile the need for both flexibility and coherence in large-scale soil protection, scientifically grounded soil health evaluation frameworks should be developed, which ensure comparability while accommodating local heterogeneity. Matson et al. (2024) provide an overview of different approaches to inferring evaluation criteria, and illustrate with the example of soil organic carbon how these approaches can lead to different conclusions about which soils are considered healthy or not. While soil, land use and climate specific benchmark values for soil organic carbon stocks are under discussion (Feeney et al. 2024), until now most other soil properties have been evaluated with uniform thresholds across Europe (Panagos et al. 2024). Moving forward, scientists need to provide recommendations for deriving context-specific evaluation criteria for all soil properties, not only soil organic carbon.

4 | Legal Certainty Versus Scientific Uncertainty

The principle of legal certainty demands that laws are clear and precise, with foreseeable implications and a degree of stability over time. Yet, meeting this fundamental principle for a law on soil is challenging given the multiple uncertainties surrounding soil functioning, soil threats, and soil management (Figure 1B).

The latest estimate of the percentage of Earth's species living in soil doubled earlier figures to 59% ± 15% (Anthony et al. 2023), illustrating not only the immense value of soil for biodiversity conservation, but also that we are only beginning to understand the complexity of soils. Soil biota are at the core of soil ecosystem health and functioning and often endangered by intensive soil management, warranting targeted protection despite scientific uncertainties in their quantitative contribution to ecosystem services. In terms of soil threats, it is plausible that emergent contaminants such as per- and polyfluoroalkyl substances (PFAS), also known as "forever chemicals" (Wang et al. 2023), and their biologically active metabolites, may interact with each other in soils or be transferred to other reservoirs, posing risks for food safety and environmental health that we do not yet anticipate. Furthermore, it is known that the fate of contaminants in soils, including their degradation, mobility and uptake in crops, may be highly variable, dependent on soil chemical and physical properties (among many other factors). To illustrate, the DT50 (time that is needed for 50% degradation) of the pharmaceutical tylosin is 3 days in a sandy soil, while it is over a year in a soil with higher organic matter content (Rietra et al. 2023). This high variability in fate of contaminants makes it challenging to assess related risks for humans and environment in changing soil conditions (Pullagurala et al. 2018; Zhang et al. 2017; Berendsen et al. 2021).

For lawmakers, we recommend the explicit inclusion of the precautionary principle as an anchor point for soil laws, providing policymakers with the possibility to act in the absence of full scientific certainty. In the proposed Directive, this principle is only mentioned in relation to Member States' defining of unacceptable risk for human health and the environment resulting from contaminated sites (Directive, art. 10(1b)), but not in relation to soil management practices and other human activities potentially detrimental to soils. Giving more weight to the precautionary principle could help provide a stronger basis for policymakers to act against practices that are likely to impact soil negatively, absent of full scientific certainty. Second, we note the importance of monitoring PFAS and other contaminants such as pesticides and antiparasitic drugs in soils more intensively. The latest news about the proposed EU Soil Monitoring Directive points to a greater inclusion of these contaminants in the monitoring requirements under the Directive, although the final details have yet to be published (European Parliament 2025).

For scientists, we identify the need to improve communication of soil knowledge, especially communicating uncertainties, in a transparent and constructive way. In this context, it is important to note that the proposed Soil Monitoring Directive includes a provision on "evaluation and review" (Directive, article 24). Through this process, a review of the Directive by the European Commission would take place 7.5 years after its entry into force, to assess the need for amendments considering new scientific knowledge. This highlights the important role for the scientific community in communicating their consolidated findings and their (dis)agreements transparently so policymakers can recognize and navigate these appropriately. However, trying to meet the need for concise messages demanded by policy makers bears risks of oversimplifying scientific results and neglecting to convey associated uncertainties. For instance, one paper on soil phosphorus, a key element of soil health, found that of 20 published soil phosphorus maps, only one met basic quality standards for communicating uncertainty (Helfenstein et al. 2024). Such omissions can lead to misinformed recommendations and hinder the effective legal consideration of uncertainties in soil management. Moving forward, scientists, law- and policymakers need to work together to discuss and navigate limitations, assumptions and remaining uncertainties across diverse disciplines. While disagreements or conflicts in science can be harmful to scientific credibility, evidence shows that communicating technical uncertainty, such as error ranges and probabilities, has no or even a positive effect on science communication (Gustafson and Rice 2020). For example, Jensen (2008) reported that scientists are perceived as more "trustworthy" if they report caveats or limitations.

5 | Property Scale Versus Spatial Interconnectedness

Land and property ownership constitute cornerstones of modern legal systems, establishing legally binding and enforceable borders between the land of different public and private actors. However, soils function within larger, interconnected landscapes where ecological processes—such as water flows and species movement—extend well beyond individual plot boundaries (Figure 1C) (van der Putten et al. 2023). This is recognized

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to some extent in the proposed Soil Monitoring Directive, with its focus on soil districts and units. Member States are responsible for establishing *soil districts* for monitoring soil health, reflecting the administrative territories under the responsibility of these governance structures, and smaller soil units, stratified according to at least soil type and land use that serve as harmonized basic data to monitor soil health with a given level of uncertainty within that soil unit (Directive, art. 4(1–2); preamble, par. 24a).

Yet, despite the Directive's unprecedented attempts to promote harmonized soil health monitoring across Member States, a deeper legal shift is needed to enable effective protection of soil. Specifically, legal frameworks need to recognize that soil functions extend beyond ownership lines, warranting laws that capture soil's broader ecological roles. Scientists can support this by integrating soil research into spatially explicit models and planning tools that link local management decisions to broader ecosystem outcomes (Delibas et al. 2021; Fossey et al. 2020). Legal experts, in turn, can help elucidate how existing legal instruments impacting soil management at the local level, for instance the EU's Common Agricultural Policy and Nitrates Directive, can be leveraged more to protect soil in tandem with the Soil Monitoring Directive. At a broader societal level, citizen councils or deliberative assemblies—bringing together cross-scale stakeholders such as farmers, landowners, community members, and experts in relevant fields such as soil science, spatial planning, and environmental governance—can deliberate over spatially explicit data, balancing local property rights with broader public interests. Outcomes might include payments for ecosystem services, cross-jurisdictional agreements, or zoning strategies that reward sustainable practices while mitigating harmful ones (Séré et al. 2024). By aligning legal instruments with the ecological, cross-scale realities of soil and engaging diverse stakeholders in decision-making, societies can more effectively protect the inherently interconnected nature of soils.

6 | Soil as Commodity Versus Soil as Non-Renewable Resource

Existing legal systems facilitate or even mandate the use of soil as an expendable commodity. Examples range from planning law (e.g., permits to construct large industrial facilities on fertile soils) to contract law (e.g., farmers bound by strict contractual obligations to supply fresh produce to retailers by pre-specified dates, even when harvesting conditions may be adverse to soil health). Indeed, legal frameworks governing soil often reflect historically dominant value systems centered on short-term productivity. Yet, both scientific and societal perspectives increasingly recognize soil as a vital, non-renewable resource with broader ecological, cultural, and long-term socioeconomic importance (Figure 1D) (Pereira et al. 2018). Nonetheless, in the latest news about the proposed Directive, the decision was announced to let go of provisions that can (indirectly) lead to more stringent sustainable soil management requirements imposed upon landowners, stating that "to protect farmers and foresters, the agreed directive does not impose any new obligations on landowners or land managers" (European Parliament 2025). Instead, the law will focus on mandating EU Member States to provide support measures, including independent advice, training activities, and capacity building, as well as the promotion of research and innovation, and measures to raise awareness of the benefits of soil resilience (European Parliament 2025).

The central challenge here thus remains aligning legal frameworks with a more comprehensive, long-term perspective on the value of soil as a multifunctional, non-renewable resource. This involves advancing scientific understanding on multiple fronts while fostering societal awareness. First, there is significant research effort needed to further elucidate and quantify the role of healthy soils for the provision of multiple ecosystem services. Second, valuing soil-based ecosystem services—assigning comparable metrics, including monetary values—can help integrate soil health into economic and legal decision-making (Pascual et al. 2015). Lessons from the forestry and water sectors, where payment for ecosystem services schemes have been implemented to monetize carbon sequestration, biodiversity conservation, and water regulation, can guide the adaptation of similar approaches for soils (Salzman et al. 2018). Here, it should not be overlooked that soils have intrinsic worth, reflect cultural heritage, and serve as historical archives—which all may hold varying significance across communities.

As science advances and societal values evolve, legal frameworks should also adapt to accommodate new knowledge and shifting priorities. In legal scholarship, it is commonly understood that law also serves an "expressive function", meaning law, if intelligently designed, may not just reflect but also positively mold societal norms and values (Kingston et al. 2021). In this light, it is high time for law to encapsulate emerging understandings of soil function, cultural significance, and long-term ecological resilience.

7 | Detecting (Non-)Compliance Versus Costly and Complex Detection

Legal rules can only achieve their intended outcomes when backed by robust detection and enforcement measures to ensure compliance on the ground. However, the interplay of above-outlined issues on uncertainty, heterogeneity, spatial interconnectedness, and the multi-faceted, long-term nature of soils makes effective detection and enforcement of non-compliance specifically costly and complex for soil (Figure 1E). Two key compliance dimensions can be distinguished: (1) "outcome-focused compliance" (e.g., is soil health sufficient?), and (2) measure-focused compliance (e.g., are land management requirements complied with?).

With respect to the first dimension, the main required outcome for Member States is setting up a monitoring system in conjunction with evaluation criteria—that is, "operational trigger values" for soil health criteria (Directive, pillar 1) and "unacceptable levels" of soil contamination (Directive, pillar 3). In other words, there is mainly an obligation to understand how healthy soils are in the Member States, leaving the goal of healthy soils by 2050 aspirational. There are several limitations to this approach. Member States are granted considerable discretion in deciding what and how much they monitor, as well as in defining what constitute "unacceptable levels". While flexibility is needed to account for the heterogeneity of soils (Figure 1A), flexibility also

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complicates legal assessments of whether Member States are meeting their obligations under the Directive. These challenges are exacerbated by a variety of monitoring (Froger et al. 2024) and soil health evaluation approaches (Matson et al. 2024), which can lead to inconsistent interpretations. It is therefore crucial again for scientists to support the legislation with (harmonized) monitoring and evaluation approaches to strengthen the scientific basis for transparent compliance detection.

Ensuring compliance with measure-focused obligations relating to soils is complicated by the costly and complex nature of detecting non-compliance on private land, as experiences with for instance the EU Nitrates Directive demonstrate (Lunn et al. 2020). In addition, there are the complicating factors of spatial drift (i.e., the movement of soil or pollutants from one location to another) and legacy issues (i.e., effects of past land uses or management practices), making it difficult if not impossible to link soil health degradation to current management practices. Detecting non-compliance with sustainable soil practices thus goes beyond soil assessments and would require reporting of comprehensive land management records, from tillage practices to pesticide use. In the final version of the Soil Monitoring Directive, provisions on sustainable land management by landowners will potentially be omitted (European Parliament 2025). Yet, for meeting the objective of healthy soils by 2050, it appears unavoidable that further binding measures will be introduced over time, mandating sustainable soil management by landowners. While legal scholarship has made important steps to unpack how environmental rules can be designed in an effective way to optimize compliance (Kingston et al. 2021) and ecological effectiveness (Alblas and van Zeben 2023), more interdisciplinary research is needed to gain a better understanding of how to design effective laws in light of such detection and enforcement challenges.

8 | The Way Forward

Designing effective soil legislation requires recognizing the inherent complexity and variability of soils, and addressing the uncertainties that persist in scientific understanding. The intricate interplay of local conditions and fundamental knowledge gaps challenges the nature of legal frameworks, which generally rely on uniform, easily enforceable standards. Instead, laws for healthy soils must embody more adaptive, principle-based approaches—anchoring minimum common standards but allowing the necessary flexibility in soil health evaluation criteria and management practices. Applying the precautionary principle where knowledge is limited, for example in addressing new or mixes of contaminants, and acknowledging that soil ecosystem services extend far beyond single properties or agricultural contexts to encompass a range of land uses and scales, are key steps in this direction. Equally important is cultivating closer collaboration between soil scientists, legal experts, policymakers, land managers, and other stakeholders to bridge their respective worlds.

Soil protection is urgent, and legislation cannot wait for perfect scientific clarity. We must therefore effectively integrate uncertainties and intricacies of soil functioning into legal frameworks. The EU's proposed Soil Monitoring Directive sets important steps in this direction, but should maintain sufficient space for iterative dialogue between scientists, law- and policymakers, continuous knowledge exchange, and the willingness to adapt as new knowledge emerges. By elucidating new ways to bridge the two worlds of law and soils effectively, we can establish legal instruments that more effectively protect soils for human and planetary health, now and in the future.

Author Contributions

Edwin Alblas: conceptualization, investigation, funding acquisition, writing – original draft, methodology, writing – review and editing, project administration, formal analysis. **Anna Edlinger:** conceptualization, investigation, funding acquisition, writing – original draft, methodology, writing – review and editing, formal analysis, project administration. **Julian Helfenstein:** conceptualization, funding acquisition, investigation, writing – original draft, methodology, writing – review and editing, formal analysis, project administration. **Maria Jose Diaz Bernal:** project administration, writing – review and editing, formal analysis. **Dienke Stomph:** formal analysis, visualization, writing – review and editing. **Bjorn Berendsen:** writing – review and editing, formal analysis. **Maria J. I. Briones:** formal analysis, writing – review and editing. **Rachel Creamer:** writing – review and editing, formal analysis. **Fenny van Egmond:** writing – review and editing, formal analysis. **Gerard Grealish:** writing – review and editing, formal analysis. **Marei Hacke:** writing – review and editing, formal analysis. **Esmer Jongedijk:** writing – review and editing, formal analysis. **Andrew Lawson:** writing – review and editing, formal analysis. **Claudia Lima:** writing – review and editing, formal analysis. **James Moloney:** writing – review and editing, formal analysis. **Liesje Mommer:** writing – review and editing, formal analysis. **Madlene Nussbaum:** writing – review and editing, formal analysis. **Stirling Roberton:** writing – review and editing, formal analysis. **Mart Ros:** writing – review and editing, formal analysis. **Barbara Tempels:** writing – review and editing, formal analysis.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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