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PERSPECTIVE

Wind erosion in European agricultural landscapes: More than physics

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Abstract

1. Wind erosion from agricultural land is an underrated and understudied environmental challenge in Europe. Its societal and policy relevance will likely increase in the near future due to climate change and associated increases in the frequency, severity and patterns of atmospheric events such as droughts.
2. We review the research on this issue and find it to be fragmented, siloed and dominated by natural sciences, leaving important research gaps. The most important gaps that circumscribe a research agenda for the future include specific effects of future climate change on wind erosion, the relevance of wind erosion for public health and ecosystem functioning, farmers' behaviour affecting erosion risk and feedback between land management and environmental change, and appropriate policy approaches to address wind erosion risks. Social science contributions are thus required to make wind erosion research relevant for addressing the related societally most pressing questions.
3. We provide a social–environmental systems perspective to highlight the potential of inter- and transdisciplinary research into wind erosion in times of climate change and the increasingly recognized need to transform agriculture towards more sustainability and climate resilience.

KEYWORDS
aeolian dust, agriculture, agri-environmental policy, air pollution, climate change, farmer behaviour, social–ecological systems, soil management, wind erosion

1 | INTRODUCTION

On 8 April 2011, 85 cars crashed and eight people died in a pile-up on German motorway A19 near Kavelstorf, Mecklenburg-Western Pomerania (Deetz et al., 2016). The immediate cause of the crash was mineral dust from wind erosion on a nearby agricultural field covering 0.79 km^2 with a bare surface, prepared for potato planting (Deetz et al., 2016). So far, in Germany, this remains the most drastic recent example of a largely underappreciated yet increasingly relevant agri-environmental challenge. In the United States, the 1930s' Dust Bowl trauma is still vivid and engrained in the collective memory (McLeman et al., 2014; Riebsame, 1986) and attention for the problem of wind erosion is present (Lee & Gill, 2015).

In Europe, potential soil loss from wind erosion was estimated by Borrelli et al. (2017), who found that more than two-thirds of arable land in the European Union were affected by wind erosion in 2001–2010 (with 4.4% being affected by high rates of soil loss). The highest mean rates were found (above 1 $Mg\,ha^{-1}\,year^{-1}$) in Northern

Europe, including Denmark, the Netherlands and the United Kingdom. Countries with highest maximum regional soil loss potential (>30 Mg ha^{-1} $year^{-1}$) in their modelling study were Denmark, Greece, Germany and the Netherlands. However, in Europe, policy and research focus much more strongly on water erosion as a land degradation threat, whereas wind erosion receives relatively little attention and is the less well-studied erosion process (Borrelli et al., 2017; Panagos & Katsoyiannis, 2019) – a situation bemoaned by Riksen et al. (2003) already almost 20 years ago.

With ongoing climate change and associated increasing risk of extreme weather events such as droughts (Samaniego et al., 2018), wind erosion is bound to become a more prominent issue on the policy and research agendas in Europe, including especially Central Europe (Borrelli et al., 2017). The understanding of soil erosion response to future climate change is, therefore, of high importance for the development of soil conservation strategies and for the protection of ecosystems. Nevertheless, the regional spatio-temporal patterns of dust emissions from wind erosion remain uncertain (Li et al., 2020).

This is particularly important in light of the significance of land and soil in addressing current environmental challenges. For instance, the report on land degradation and restoration of the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that “degradation of the Earth's land surface through human activities is negatively impacting the well-being of at least 3.2 billion people” (IPBES, 2018), which resonates with the recognized manifold potential contributions of land and soil to Sustainable Development Goals (SDGs; Keesstra et al., 2016). Soil degradation implies the loss of multiple functions central to human well-being (Helming et al., 2018). However, this is barely reflected in EU policy documents, where soil and, especially, wind erosion are present implicitly at best (Montanarella & Panagos, 2021). The recently published EU Soil Strategy does not mention wind erosion once (EC, 2021).

In this article, we provide a broad perspective on the societal challenge of wind erosion and the state of research related to it. We identify a number of research gaps in the current understanding of wind erosion in Europe. These gaps include the effects of climate change on wind erosion; the relevance of wind erosion for public health, ecosystem functioning and other off-site costs; the awareness of wind erosion and the associated costs among farmers, policy-makers and the broader public; farmers' behaviour affecting erosion risk and feedbacks between land management and environmental change; appropriate policy approaches to address wind erosion risks; and the role of citizen science in establishing a firmer knowledge base. Building upon this gap analysis, we emphasize three issues: first, wind erosion is an increasingly important yet underestimated and understudied challenge in Europe; second, wind erosion should be viewed from a holistic perspective as a social–environmental phenomenon; third, this social–environmental perspective requires interdisciplinary research efforts on a much broader scale than currently.

The article is structured as follows: first, we introduce relevant basic principles of wind erosion. Second, we provide an overview of the state of art of wind erosion research. Third, we identify a number of research gaps, with a particular focus on Europe. Fourth, we introduce the perspective of social–environmental systems to demonstrate its relevance for the analysis of wind erosion. We use this perspective to discuss the implications of the identified research gaps for future research and policy.

2 | BASIC PRINCIPLES OF WIND EROSION AND DUST PRODUCTION

To understand the implications of wind erosion in different domains of the social–environmental system, a basic understanding of the environmental processes involved is needed. Dust aerosol particles, that is, tiny soil particles suspended in the air (0.1 μm to >100 μm), are entrained into the atmosphere by wind. Thereby, dust uplift (entrainment) itself can be seen as a threshold problem: if the momentum provided by wind and turbulence is sufficiently high, soil particles are set into motion and may ultimately be injected into the atmosphere. The amount of energy needed to foster dust entrainment is determined by soil characteristics (i.e. soil type, texture, soil moisture), the presence of crusts, vegetation and snow cover. Altogether, the soil properties determine the susceptibility of the soil surface to wind erosion and ultimately the likelihood for dust emission. Whereas some soil characteristics such as soil type are static over time (inherent soil properties, Vogel et al., 2019), the presence of crusts, vegetation and snow may change during the course of a year as well as interannually. The latter, short-term variability in soil conditions is impacted by natural environmental variability, but also human-induced changes in environmental parameters that affect the susceptibility of the soil surface to wind erosion (manageable soil properties). It should be noted, however, that even the inherent soil properties can change due to erosion events, if the upper layers of soil are removed.

Major areas that exhibit a high susceptibility to dust entrainment and wind erosion are arid and semi-arid drylands in Africa, Asia, Australia, North America and South America (Schepanski, 2018). For the US, these are in particular the states west of 100° W, such as the interior upper western states and the south west. China has large desert and steppe areas in particular in the west and north. Although semi-arid, large parts of these regions are agriculturally used. In comparison, Europe has been less affected by wind erosion (Borrelli et al., 2017). However, as will be discussed below, the importance of this problem is likely to increase in the near future in Europe as well.

While susceptibility to wind erosion is driven to a large extent by natural factors, it is also strongly influenced by land management choices. Management practices affecting susceptibility to soil erosion include the temporal extent of vegetation cover and residue management, crop choice and crop rotation, tillage (including its timing with regard to weather conditions and time of day), field size, landscape elements (especially windbreaks, such as hedges or tree lines determining the fetch) and fertilizer application (Nordstrom & Hotta, 2004; Rosa-Schleich et al., 2019). Generally, wind erosion occurs mostly from bare soil. A largely continuous cover of the soil with crops or plant residues throughout the year can, therefore, reduce the wind erosion potential significantly. Windbreaks can reduce the wind speed on soil level, thus reducing the amount of lifted particles. The effectiveness of windbreaks declines with increasing distance from their location; a reduction of the field size, therefore, decreases the acceleration area of the wind. This is partly recognized in policy: for instance, the Good Agricultural and Environmental Conditions (GAEC) rules, which farmers receiving direct payments within the European Union's Common Agricultural Policy (CAP) are required to adhere to, include measures targeting soil erosion: tillage management (GAEC 5) and minimum soil cover (GAEC 6; European Union, 2021). However, these rules remain pretty general (not differentiating among erosion types) and selective in terms of management prescriptions.

3 | WIND EROSION RESEARCH LANDSCAPE

Currently, wind erosion and aeolian dust research have a number of foci. Dust sources are separated into different types reflecting their genesis: natural, hydrologic (formed by water) and anthropogenic (human-induced; Ginoux et al., 2012). Environmental changes due to climate change that affect the efficiency of dust sources and their spatio-temporal distribution are considered, and particularly vulnerable source regions are examined regarding their interannual variability and possible drivers of this. Thereby, soil characteristics, meteorological conditions and the occurrence of dust emission determining atmospheric circulation patterns are brought into perspective and discussed with regard to their implication on the Earth system in general and human well-being in particular (Webb & Pierre, 2018). A bibliometric analysis (to be found in the Supplementary Material) shows that the landscape of wind erosion research is fragmented along disciplinary and geographical dimensions.

3.1 | Disciplinary fragmentation

The disciplinary fragmentation is related to thematic clusters, such as agricultural management, air quality, drought and desertification. While there is exchange between the clusters, it is not particularly strongly pronounced. Also, there is a general paucity of contributions from social sciences. Meanwhile, feedbacks of dust aerosol in the climate system are manifold and diverse with regard to impact and scale – and thus require different research disciplines to address them (Field et al., 2009). For example, dust aerosol impacts on cloud formation and the Earth radiation balance, which involves physics and related disciplines. The study of dust impacts stemming from its role as micronutrient is addressed by geobiochemical research. Air quality concerns, impacts on infrastructure, transport (ground-based and airborne traffic), the economy, human health and ecosystems, illustrate the relevance of dust in the Anthropocene, ultimately underlining the demand for interdisciplinary research concepts reflecting the cross-disciplinary relevance of dust. However, most studies in the extant literature are primarily disciplinary and only seldom bridge disciplines.

3.2 | Underrepresented Europe

The United Statesand China are the main wind erosion research hubs, while European and other countries are much less represented. Europe is less obviously prone to wind erosion than the United States or China, and it does not have the history of extreme erosion events (such as the Dust Bowls). Wind erosion has not received sufficient research attention yet, despite efforts in pan-European analyses of wind erosion potential from the Joint Research Centre (JRC) of the European Commission (Borrelli et al., 2016, 2017) and more regionally focused analyses e.g. in Hungary (Mezősi et al., 2015) or Germany (Zutz, 2015). Figure 1 reproduces the most advanced analysis of wind erosion risk in Europe (more specifically, EU) that we are aware of, which focuses on the soil loss potential given recent climatic conditions (Borrelli et al., 2017). In contrast, water erosion seems to be pre-dominant concerning the number of publications, data, models, knowledge and ongoing field experiments (Panagos & Katsoyiannis, 2019). Still, according to the European Commission approximately 42 million hectares in Europe are influenced by wind erosion (EC, 2006). While the soils of European countries along the Northern Sea coast show high susceptibility to erosion, Borrelli et al. (2016) find that considering the amount of days with erosive climate conditions, southern European countries seem to be in greater risk of wind erosion. There is still much research to be done in Europe if the information base on wind erosion is to be comparable to the comprehensive understanding of water erosion.

4 | GAPS IN EUROPEAN WIND EROSION RESEARCH

Based on a broad overview of the wind erosion literature, a number of crucial gaps in European wind erosion research can be identified. Building upon the expertise of the author team in atmospheric modelling, human and physical geography as well as environmental economics, we highlight 10 major research gaps (denoted below inline by [RG#], where # is a running number), which are summarized in Table 1.

4.1 | Wind erosion risk and climate change

Future risk of wind erosion in Europe, accounting for climate change, has not been quantified [RG1]. The complexity of the processes of predicting climate and soil data make it difficult to take into account future climate change impacts on wind erosion processes (Sharratt et al., 2015; Tegen & Schepanski, 2018). While projections exist for the response of water erosion risk to climate change (Borrelli et al., 2020), to our knowledge no comparable studies have addressed

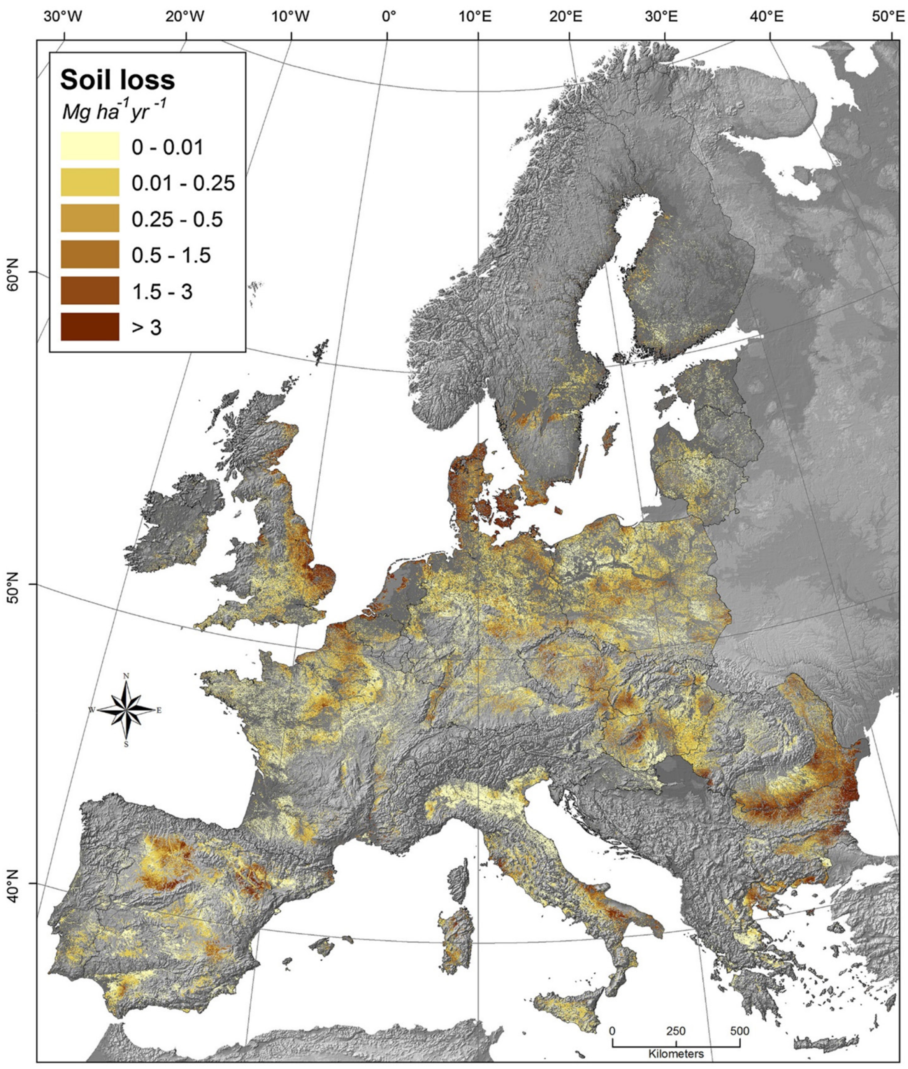

FIGURE 1 Potential soil loss due to wind erosion from EU arable land without climate change (Source: Borrelli et al., 2017)

TABLE 1 Research gaps for European wind erosion research

RG1: What is the future risk of wind erosion, given climate change?
RG2: What is the magnitude of on-site and off-site (economic) costs of wind erosion?
RG3: What are the health impacts of air pollution due to agricultural wind erosion?
RG4: What are the off-site ecosystem impacts of agricultural wind erosion?
RG5: What factors influence societal and policy awareness of wind erosion risks?
RG6: What factors influence farmers' awareness of wind erosion risks?
RG7: What factors affect farmers' behaviour that influence wind erosion potential on their land? How is this behaviour affected by other objectives?
RG8: What are trade-offs and co-benefits involved in erosion-mitigating measures? (e.g. wind erosion mitigation and climate adaptation)
RG9: What are appropriate policy responses to wind erosion risks?
RG10: How to harness the potential of transdisciplinary research and citizen science for a better understanding of and effective societal responses to wind erosion?

wind erosion at the European scale so far. At the EU level, data relevant for soil erosion studies that is available through the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu) and the European Soil Data Centre (ESDAC, https://esdac.jrc.ec.europa.eu/) is mainly related to parameters relevant primarily for water erosion. However, the increase in air temperature induced by climate change is likely to affect soil erosion indirectly in several ways, including variations in crop biomass and soil moisture, which influence the vulnerability of the soil to wind erosion (O'Neal et al., 2005). In central Europe, increased aridity and more frequent extreme wind speed events will probably lead to an enhanced wind erosion of fine-texture soils (EEA, 2012). In extreme cases, erosion events may even affect the inherent soil properties (Vogel et al., 2019).

4.2 | Costs of wind erosion

The same risk of wind erosion can translate into different on-site and off-site costs of actual erosion events, depending on multiple factors such as the agricultural productivity of the affected area or its proximity to human dwellings. Knowledge of these costs can help to communicate the societal importance of wind erosion and also to compare it to other environmental challenges. On-site costs are understood here as the costs arising from soil *loss* due to wind erosion, leading ultimately to loss of soil functions; off-site costs refer to costs caused by translocation of eroded particles, usually in the form of *dust*, and the associated air pollution, sedimentation and contamination of water bodies (Middleton et al., 2019). Actions implemented by farmers on-site reduce costs of erosion both for themselves and for the society. In an analysis of the macroeconomic impacts of *water* erosion in the EU, Panagos et al. (2018) arrived at an estimate of more than 150 million € per year GDP (gross domestic product) reduction. A comparable estimation of the costs of wind erosion is currently missing [RG2].

On-site effects of wind erosion can cause considerable costs for farmers, including damage and loss of soil, crops, and farming equipment. In consequence, the economic effects of wind erosion like the loss of fertilizer or plants need to be compensated by the farmers (Riksen & de Graaff, 2001); as a response, they often increase their use of fertilizers to compensate for the loss in soil productivity due to wind erosion. In the short term, this may seem cheaper than actually implementing erosion control measures, which may cause high costs for the farmer (Nordstrom & Hotta, 2004). However, in the long term, such control measures would effectively reduce the risk and costs of wind erosion (Riksen & de Graaff, 2001), while also helping to avoid off-site effects of wind erosion events.

The estimation of off-site costs of wind erosion is an especially great challenge for research, as many factors interact, making it difficult to quantify the contribution of each. Off-site costs can be related to impaired visibility (leading to traffic accidents), ambient air pollution (resulting in public health impacts; Riksen & de Graaff, 2001) and damage to ecosystems through sedimentation and contamination of water bodies (Middleton et al., 2019). Pozzer et al. (2017) find that a simulated reduction of agricultural dust emissions would lead to a decrease of the air pollution related mortality of the European population. In addition, the transport of microplastics (Bento et al., 2017) and other problematic substances such as glyphosate (Rezaei et al., 2019) has been raised as potential health and ecosystem hazards related to wind erosion from agricultural land. While such findings currently bear high uncertainties, they underline the importance of the wind erosion phenomenon for human well-being. Agricultural dust is not the main source of air pollution, yet its relative contribution has remained relatively stable while other sources have been reduced. For instance, in Germany, agriculture is now the second largest source of dust with a ca. 15% share, while its contribution in 1990 was only around 3% (at comparable absolute values).[1] Off-site health impacts [RG3] and ecosystem impacts [RG4] of agricultural dust emissions are major research gaps in wind erosion research that require quantification, monitoring as well as operational and user-friendly modelling of air pollution through wind erosion, especially in the vicinity of human settlements and infrastructure (Webb et al., 2020). This includes providing real-time, site-specific information on wind erosion potential, to prevent events with particularly high on-site and off-site costs.

4.3 | Complexity and societal awareness

While we do not know exactly the extent of on- and off-site effects that are detrimental to human well-being, we know enough to appreciate the multitude of potential effects. Furthermore, despite the lack of projections of future wind erosion risks given climate change, there is enough evidence and understanding of the phenomena involved to be concerned about increased future risks due to the expected rise in dry periods and wind speeds (Tegen & Schepanski, 2018; Webb & Pierre, 2018). Nonetheless, we observe a persistent lack of attention to the problem in European society and policy. For instance, air pollution measurements do not even separate between agricultural, mineral dust and other aerosol sources. This lack of attention to wind erosion in Europe may be related to the diffuse nature of the phenomenon, which is characterized by tipping points at various levels. On the geobiophysical side, a set of conditions have to be fulfilled to trigger an erosion event. The ideal dust source is dry, barely covered by vegetation or snow and consists of a mixture of very fine dust particles and somewhat larger sand grains. If a patch of bare soil susceptible to wind erosion experiences wind speeds sufficiently high for individual soil particles to be mobilized, a dust plume may develop. Whether a mature dust storm forms depends on the strength and persistence of the wind conditions, the amount of erodible material, and how easy it can be eroded. While the former is determined by the general atmospheric circulation and the resulting local meteorological condition, the latter is determined by soil type and texture (Schepanski, 2018).

Such major events attract attention and convey the importance of the challenge – transformative regime shifts in management of natural resources such as agricultural soils can be triggered by “traumatic” events such as the US-American Dust Bowl of the 1930s (McLeman et al., 2014; Riebsame, 1986) and can result in transformation of attitudes, policies, management practices and, ultimately, the ecosystem. However, non-major events are problematic as well – loss of soil functions can also be caused by more gradual, “invisible” sequences of small erosion events. Here, the diffuse nature of the phenomenon is important once more. When it comes to air pollution, there is a spectrum between clearly attributable anthropogenic sources (e.g. industrial dust) and similarly clearly attributable natural emissions (e.g. dust from steppes or deserts). Aeolian dust from agricultural land is somewhere between the two, as anthropogenic and natural factors interact and attribution is difficult. Another historical example of such detrimental interaction of anthropogenic and natural factors was the Aral Sea case, where drainage for irrigation led to wind erosion and dust emissions both from dried up lake area and from the agricultural fields, which had been created with the help of the irrigation water that then stopped flowing (Micklin, 2007). Overall, the exact reasons for limited awareness of challenges associated with wind erosion in policy and public debate are not well understood [RG5].

4.4 | Awareness and behaviour of farmers

Farmers' awareness of the risks of wind erosion is similarly understudied – in contrast to the good availability of research into farmers' perceptions of erosion in developing countries (Touré et al., 2020), we are not aware of analogous studies in Europe [RG6]. Stronger involvement of both farmers and those potentially affected by air pollution from agricultural dust in wind erosion research seems crucial. Moreover, from a policy perspective, the role of farmers' behaviour, especially adoption of soil protecting practices, is central. While we are not aware of research into farmers' behaviour with respect to wind erosion specifically, much can be learned from related studies into the determinants of farmers' adoption of environmentally friendly practices. Contrary to conventional wisdom, farmers' environmentally relevant behaviour cannot be reduced to economic motivations (Bartkowski & Bartke, 2018); rather, it is determined by a complex set of factors, including of course economic considerations (monetary costs and benefits), but also non-economic barriers (e.g. path dependencies or legal constraints) as well as personal attitudes, values, self-identity, social norms, knowledge and beliefs. Also, there may be differences in the willingness and ability to adopt incremental (e.g. planting a hedge) versus broad changes in management (e.g. a shift to no-till). Given the interplay of many different factors in wind erosion (e.g. on- and off-site effects), there is an urgent need for dedicated research into farmers' behaviour and attitudes towards this particular environmental challenge [RG7].

4.5 | Co-benefits of management options

Research on management practices that reduce wind erosion risks usually focuses predominantly on erosion-related benefits and risks. For example, in their discussion of "methods of controlling sediment loss from fields", Nordstrom and Hotta (2004) refer to interactions with other goals only once, when briefly addressing the windbreaks use up agronomically valuable space. However, the co-benefits and trade-offs involved in practices and measures reducing wind erosion risk can be substantial. For instance, introduction of landscape elements as windbreaks can have multiple positive public ecological benefits such as increases in biodiversity (Tschumi et al., 2020; Vanneste et al., 2020) but also aesthetics and recreational potential (Hermes et al., 2018). Scarce evidence suggests that there are significant public benefits from erosion prevention, which go well beyond the private benefits to farmers (Colombo et al., 2005; Middleton et al., 2019). From the point of view of farmers as well as broader society, the much advertised potential contribution of soils to climate change mitigation via carbon sequestration and "negative emissions" would also reduce proneness to wind erosion by increasing the water content of soils (Amelung et al., 2020; Baveye et al., 2020). Conversely, mechanical soil management under dry conditions increases the risk of wind erosion; however, under wet conditions, it contributes to soil compaction (Schjønning et al., 2015; Schröder et al., 2020). Nonetheless, there is currently a paucity of studies addressing the trade-offs and synergies in the context of wind erosion explicitly [RG8], though erosion control (wind and water erosion) is sometimes addressed in broader studies of the environmental effects of various management strategies (Rosa-Schleich et al., 2019).

4.6 | Policy options

Given the above mentioned complexities, broad and holistic analyses are required to raise awareness and inform the design of proactive policy responses [RG9] that can serve as leverage points for transformations towards sustainability (Chan et al., 2020). Such policy responses may include rewarding farmers for the adoption of appropriate management practices minimizing erosion risk while also maximizing co-benefits, for example, in terms of negative emissions. Particularly, research combining the effects of climate change on wind erosion risks and a view on their interaction with climate change adaptation and other major socio-economic drivers of natural resource use has large potential here. Approaches such as scenario analysis (Mitter et al., 2020) or coupled modelling (Robinson et al., 2018) have large potential in this context, also due to their inter- and transdisciplinary character (Schlüter et al., 2019). In this context, the effects of various policy interventions on farmers' behaviour and, ultimately, the incidence and distribution of on-site and off-site costs of wind erosion can be analysed.

4.7 | New sources of data

To grasp the complexities involved in wind erosion better, improved measurement and modelling (including coupled social–environmental models) is required. For instance, in addition to public agencies working on land management, across the world programmes and networks like DustWatch (Leys et al., 2008) and the US National Wind Erosion Research Network offer new insights for modelling land management related to wind erosion (Webb et al., 2016; Webb & Pierre, 2018) and often combine scientific research with citizen participation. Citizen science, for example, by involving farmers in the observation and measurement of wind erosion events, has a large potential here. Such projects have proven to increase awareness of erosion and result in improved data collection (Leys et al., 2008); however, comparable approaches are still missing in Europe. Nevertheless, new implemented data centres such as the European Copernicus Climate Change Service (C3S, https://climate.copernicus.eu) aim at providing scientific data sets that encourage scientists to tackle climate-change-related questions such as soil erosion. Coupling social and environmental models fed by these data would allow the joint consideration of the whole chain of events from climate change impacts to the probability of wind erosion events and associated local loss of soil functions to the probability of dust creation and transport with the associated health risks, including feedbacks through policy and management changes. The complexity of the social–environmental phenomenon wind erosion needs to be matched by a holistic, interdisciplinary approach to studying it, especially if the goal is to generate policy-relevant knowledge [RG10].

5 | WIND EROSION AS A SOCIAL–ENVIRONMENTAL PHENOMENON

The discussion above already hints that wind erosion is an understudied, multidimensional phenomenon whose causes and consequences span both social and environmental systems. For an improved understanding of drivers and outcomes of wind erosion and for identifying appropriate management and policy options, reframing the wind erosion problem from a social–ecological systems perspective would be of great benefit (note that we build upon the perspective of the social–*ecological* systems literature while using the term social–*environmental* system in the following, which seems more appropriate given the largely abiotic nature of wind erosion). To successfully leverage such a perspective, inter- and transdisciplinary research is required (Baum & Bartkowski, 2020). In this, we go well beyond the current, disciplinarily narrow focus of most wind erosion literature, where even a call for "holistic perspective" only means combining the insights of multiple natural science disciplines (Field et al., 2009). Above all, we argue that wind erosion requires a much stronger engagement from and with social scientists and, with their help, also the involvement of stakeholders.

The view of wind erosion as a social–environmental phenomenon puts emphasis on strongly interdependent and (inter)linked systems of people and nature, which are nested across temporal and spatial scales (Fischer et al., 2015; Metzger et al., 2021; Reyers et al., 2018). Social–environmental systems (SES) are complex adaptive systems, where individual behaviour of the entities of the system (both human and environmental entities) is interlinked via feedbacks and where these entities adapt and transform in response to changes in the social and geo-biophysical environment. The SES perspective helps uncover non-obvious interdependencies, feedbacks uncertainty and trade-offs within and across social and environmental subsystems, while also allowing to explicitly consider non-linear behaviour and therewith the occurrence of tipping points.

The social–environmental system 'agricultural landscape' is embedded in the larger atmospheric and climatic system (Figure 2).

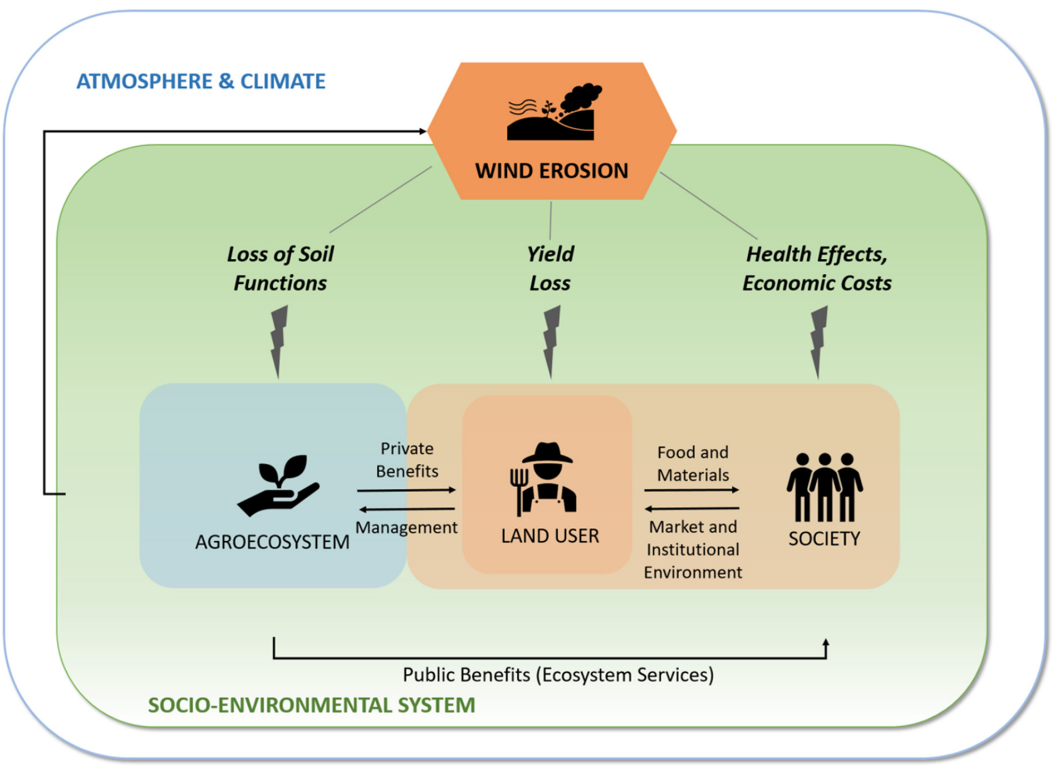

FIGURE 2 Conceptual framework of wind erosion as a social–environmental phenomenon

Therefore, the future risk of wind erosion in the face of climate change is a central research gap, including the associated feedbacks and interactions between wind erosion, climate change mitigation and adaptation. There is a need to expand Europe-focused analyses of wind erosion potential (Borrelli et al., 2017) by coupling them with climate scenarios to generate projections of future changes in susceptibility of European agricultural land to wind erosion, mimicking and expanding similar efforts in the context of water erosion (Borrelli et al., 2020; Panagos et al., 2021). Given this starting point, the SES perspective can illuminate a number of further issues related to the research gaps summarized in Table 1, of which we would like to emphasize two: feedback loops among the components of the system; and the potential of transdisciplinarity in studying the system holistically.

The focus on feedbacks within the system suggests a 'window of opportunity' for science and policy, given the currently high salience of climate-change related challenges in societal and policy debates. Specifically, ongoing climate change is likely to induce shifts (increases) in the economic costs of soil erosion, within both the social subsystem (yield loss, health effects, further economic costs) and the agroecosystem (soil function loss; Helming et al., 2018) [RG1, 2]. Especially the health impacts of air pollution related to aeolian dust from agricultural land, including impacts of toxins and pathogens carried by agricultural dust (Middleton, 2017; Thiel et al., 2020) [RG4], may induce a higher awareness of the overall problem among the public [RG5]. At the same time, climate change impacts are already now forcing farmers in Europe and elsewhere to adapt their management (Meuwissen et al., 2019). Depending on the choice of adaptation strategies, different trade-offs or synergies with wind erosion control may arise (Webb et al., 2017) [RG6, 7, 8]. Policy can play a major role here in providing incentives for those strategies that minimize trade-offs and maximize synergies and co-benefits [RG9]. Moreover, shifts in awareness, perception and preferences of the public [RG5], triggered by the increasing visibility of impacts but also possibly by citizen science approaches [RG10], are likely to result in shifts in erosion-related policy [RG9], which will then interact with the adaptation strategies of farmers, ideally leading to a maximization of synergies and co-benefits [RG7, 8]. Understanding these feedbacks and studying each issue while being aware of the interlinkages within the social–environmental system will allow to generate societally and policy-relevant knowledge, for which this paper has sketched a research agenda.

This leads us to the other important contribution of the SES perspective, namely the centrality of transdisciplinary research approaches. Here, we put a particular emphasis on harnessing farmers' local knowledge and their involvement in co-creation of new knowledge (e.g. in combination with citizen science projects; Schneider et al., 2012, 2019). Farmers are often constrained by economic and legal factors, which in extreme cases may lead to path dependencies preventing the adoption of erosion-reducing practices. Involving them in transdisciplinary research efforts would allow taking their 'action space' to adopt such practices better into account (Gütschow et al., 2021). This would help design policies that maximize available synergy and co-benefit potentials between climate change adaptation, wind erosion control and the multiple private and public benefits provided by agricultural landscapes (e.g. permanent soil cover may help conserve soil moisture, creating a beneficial feedback loop; hedges planted as windbreaks can harbour biodiversity). Thus, studying wind erosion can be embedded in the broader effort to understand and foster a transformation of agriculture towards sustainability.

AUTHOR CONTRIBUTIONS

All authors conceived the ideas; Bartosz Bartkowski led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors are not aware of any conflict of interest associated with this article.

DATA AVAILABILITY STATEMENT

There are no data associated with this article.

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ENDNOTE

[1] Own calculation based on: https://www.umweltbundesamt.de/sites/default/files/medien/384/bilder/dateien/3_tab_emi-ausgew-luftschadst_2022.pdf (accessed 29 November 2022).

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SUPPORTING INFORMATION

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