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Unrecognized threat to global soil carbon by a widespread invasive species

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Abstract

Most of Earth's terrestrial carbon is stored in the soil and can be released as carbon dioxide (CO_2) when disturbed. Although humans are known to exacerbate soil CO_2 emissions through land-use change, we know little about the global carbon footprint of invasive species. We predict the soil area disturbed and resulting CO_2 emissions from wild pigs (*Sus scrofa*), a pervasive human-spread vertebrate that uproots soil. We do this using models of wild pig population density, soil damage, and their effect on soil carbon emissions. Our models suggest that wild pigs are uprooting a median area of 36,214 km^2 (mean of 123,517 km^2) in their non-native range, with a 95% prediction interval (PI) of 14,208 km^2–634,238 km^2. This soil disturbance results in median emissions of 4.9 million metric tonnes (MMT) CO_2 per year (equivalent to 1.1 million passenger vehicles or 0.4% of annual emissions from land use, land-use change, and forestry; mean of 16.7 MMT) but that it is highly uncertain (95% PI, 0.3–94 MMT CO_2) due to variability in wild pig density and soil dynamics. This uncertainty points to an urgent need for more research on the contribution of wild pigs to soil damage, not only for the reduction of anthropogenically related carbon emissions, but also for co-benefits to biodiversity and food security that are crucial for sustainable development.

KEYWORDS
biological invasion, bioturbation, climate change, CO_2 emissions, ecosystem engineer, soil disturbance, ***Sus scrofa***, ungulate, wild boar, wild pig

Resumen

La mayor parte del carbono en la biosfera terrestre esta almacenado en el suelo y al ser perturbado, se libera como dióxido de carbono (CO_2). La actividad antropogénica que ha exacerbado las emisiones del carbono del suelo es el cambio de uso de suelo, sin embargo nuestro conocimiento sobre la liberacion del carbono del suelo por parte de especies invasoras es aun limitado. Hemos predecido el area de suelo perturbada por los cerdos salvajes (*Sus scrofa*) y las emisiones de CO_2 resultantes de dicha actividad. El cerdo salvaje es uno de los vertebrados mas destructivos a nivel global que excavan el suelo en busqueda de comida. Hemos utilizado modelos de densidad

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poblacional de cerdos salvajes, perturbación del suelo y su efecto en las emisiones del carbono del suelo. Nuestros modelos sugieren que los cerdos salvajes excavan un area media de 36,214 km^2 (promedio de 123,517 km^2) en su area no nativa, con un intervalo de prediccion (PI) del 95% de 14,208 km^2–634,238 km^2. Esta perturbación al suelo da como resultado emisiones medias de 4,9 millones de toneladas métricas (MMT) de CO_2 por año (equivalente a 1.1 millones de vehículos de pasajeros o 0,4% de las emisiones anuales del uso de la tierra, cambio de uso de la tierra y silvicultura; promedio de 16.7 MMT) pero es bastante incierto (95% PI, 0.3–94 MMT CO_2) debido a la variabilidad en la densidad de los cerdos salvajes y la dinámica del suelo. Esta incertidumbre apunta a una necesidad urgente de más investigación sobre la contribución de los cerdos salvajes a la perturbacion del suelo, no solo para la reducción de las emisiones de carbono antropogénicas, sino también para los beneficios colaterales para la biodiversidad y la seguridad alimentaria que son cruciales para el desarrollo sostenible.

1 | INTRODUCTION

The majority of Earth's terrestrial carbon is stored in the soil (Lal, 2004). When disturbed, soil organic carbon (hereafter, "soil carbon") can be lost through emissions into the atmosphere in the form of carbon dioxide (CO_2) (Lal, 2004). The most acknowledged human drivers of soil disturbance and carbon emissions are agricultural cultivation and production (Amundson et al., 2015; Sanderman et al., 2017) and habitat degradation from development (Pataki et al., 2006). Despite substantial scientific attention on the importance and causes of soil CO_2 emissions in recent decades (Bossio et al., 2020; Lal, 2004; Vermeulen et al., 2019), there are human-mediated impacts on soil that remain unexplored. Indeed, a potential source of anthropogenic soil carbon emissions is invasive species, with research suggesting human-spread animals ranging from insects like mountain pine beetles and burrowing earthworms to mammalian herbivores such as cattle, deer, goats, rabbits, and pigs cause severe alterations to soil properties through vegetation loss and direct soil disturbance (Barrios-Garcia & Ballari, 2012; James & Eldridge, 2007; Peltzer et al., 2010; Sitters et al., 2020). Yet, their global effects on soil and resulting CO_2 emissions—especially in areas where they are currently invading—are lacking.

We assess the global ramifications of one of the most extensive human-spread species, wild pigs (*Sus scrofa*), on soil disturbance and CO_2 emissions. Wild pigs are ecosystem engineers, causing soil damage via digging for belowground plant parts, fungi, and invertebrates (Barrios-Garcia & Ballari, 2012; Figure 1). Wild pigs have been introduced to all continents except Antarctica (Barrios-Garcia & Ballari, 2012), with their non-native range continually expanding (Snow et al., 2017), leading to not only a current large potential for soil damage (Barrios-Garcia & Ballari, 2012; Bueno et al., 2013; Hone, 2012; Liu et al., 2020; Risch et al., 2010; Figure 2), but a looming unrecognized contributor to global soil carbon emissions. Here we predict wild pig densities in their current non-native range and calculate the proportion of land area and resulting CO_2 emissions. Our model leverages existing knowledge on the relationship between wild pig density and soil disturbance (Hone, 2002, 2012) and the effects of wild pig soil perturbation on carbon emissions (Cuevas et al., 2012; Liu et al., 2020; Persico et al., 2017; Risch et al., 2010), providing a global estimation of affected soil area and the contribution of wild pigs to soil CO_2 emissions.

2 | MATERIALS AND METHODS

We determine the soil area and soil CO_2 emissions from wild pigs within their current non-native geographic distribution by first predicting wild pig densities per pixel (1-km^2 resolution) using a linear model from Lewis and colleagues (Lewis et al., 2017). The Lewis et al.

FIGURE 1 Invasive wild pigs (*Sus scrofa*). Wild pigs are one of the most widespread and abundant human-spread mammals globally. They are prolific ecosystem engineers, disturbing soil via digging for belowground plant parts, fungi, and invertebrates. Photo credit: Pixabay

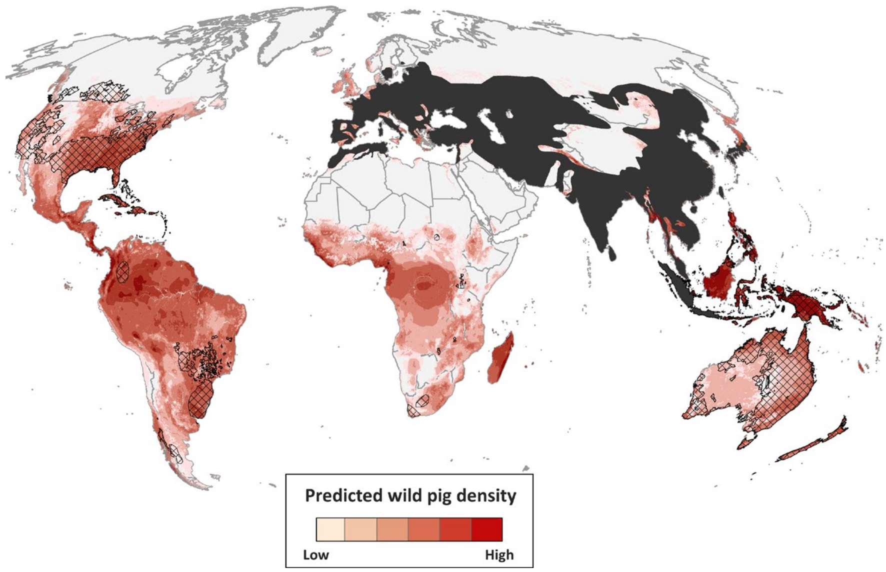

FIGURE 2 Predicted population densities and distribution of invasive wild pigs (*Sus scrofa*). Global predicted wild pig densities (from Lewis et al., 2017), with low representing <1 individual km^{-2} and high representing >11 individuals km^{-2}. The hatched areas represent the current non-native distribution of wild pigs (from Lewis et al., 2017), which is the spatial extent used for our analysis. Although our analysis focuses on their current non-native distribution, wild pigs have the potential to expand outside of these areas (the non-hatched and red-shaded areas). The black-shaded areas represent the native distribution as determined by the International Union for Conservation of Nature (IUCN, 2020)

model is based on known records of 129 log-transformed wild pig densities across five continents (Supplementary Methods, Step 1). Predictor variables in the model are seven biotic and abiotic factors across the 129 locations. Biotic factors include large carnivore richness (predation risk) and vegetation structure, and abiotic factors include potential evapotranspiration and precipitation. However, to incorporate uncertainty associated with density, we do not use the single set of best fitting coefficients in the above model. Instead, we simulate 10,000 sets of coefficients from probability distributions derived from their model, implemented in R (R Core Team, 2019) (Supplementary Methods, Step 1). Each set of coefficients produces a different map of estimated wild pig densities that are used to inform subsequent steps.

We then calculate the relative proportion of ground disturbed as a function of wild pig density per pixel parameterized from a 15-year study of wild pig soil disturbance. The long-term study was conducted across 700 sampling plots that represented a range of climatic conditions, vegetation types, and elevations spanning lowland grasslands to sub-alpine woodlands (Hone, 2002, 2012) (Supplementary Methods, Step 2). Because there is uncertainty associated with the effects of pig density on soil disturbance, we simulate 10,000 sets of model parameters for the soil disturbance model from a lognormal distribution such that each simulated pig density corresponds to an estimated proportion of land disturbed (Supplementary Methods, Step 2). The resulting 10,000 estimates of soil disturbance from wild pigs per pixel are then used for subsequent estimates of CO_2 emissions.

Next, we estimate the annual soil CO_2 emissions from wild pig soil disturbance in metric tonnes by firstly multiplying the proportion area disturbed with the estimated CO_2 emissions from soil derived from Raich and colleagues' global soil respiration data (Raich et al., 2002) (Supplementary Methods, Step 3). Then we multiply the relative amount of natural soil CO_2 emissions from Raich et al. by an estimated proportion increase in those emissions as a result of wild pig soil disturbance. Due to the paucity of research associated with the proportion increase in soil CO_2 emissions from wild pig soil disturbance (Cuevas et al., 2012; Liu et al., 2020; Persico et al., 2017; Risch et al., 2010) we draw from a uniform distribution across 10,000 simulations, with a minimum of 0 and maximum of 0.695. The minimum value is zero because there may be cases where annual soil CO_2 emissions are negligible or unlikely under disturbance (e.g., extremely dry or wet environments may have little or no additional respiration under disturbance) (Cuevas et al., 2012; Persico et al., 2017). The maximum estimated proportion increase is based on the highest known annual effect of wild pig soil disturbance on soil CO_2 emissions (Liu et al., 2020). We assume that the effect of wild pigs on emissions is already reflected in the Raich et al. data, so we divide our estimate by one plus the estimated proportion increase from wild pig soil disturbance to determine the final estimate of CO_2 emissions from wild pigs per simulation per pixel (Supplementary Methods, Step 3).

To reduce the risk of over-estimating soil CO_2 emissions from soil disturbance, we remove pixels that overlap with all tillage croplands and human built-up areas (Supplementary Methods, Step 4). Finally, we sum results across pixels for each simulation and determine the 95% prediction interval by taking the upper and lower 2.5% value from the 10,000 simulated results. More details regarding our approach can be found in the Supplementary Methods.

3 | RESULTS

Wild pigs are disturbing soil across terrestrial Earth, with a median area of 36,214 km^2 (the size of Taiwan) and a mean area of 123,517 km^2 (roughly the size of Nicaragua) per year. But the 95% prediction interval (PI) suggests the damaged extent is highly uncertain (95% PI, 14,208–634,238 km^2). Within this disturbed area, the median estimated contribution of wild pigs to annual CO_2 emissions is 4.87 million metric tonnes (MMT), which is equivalent to the emissions of 1.1 million passenger vehicles (US EPA, 2018) or 0.4% of annual emissions from land use, land-use change, and forestry (Le Quéré et al., 2018). The estimated mean annual emissions from wild pig soil disturbance are 16.97 MMT CO_2 (Figure 3), which is equivalent to 3.7 million passenger vehicles or 1.3% of annual emissions from land use, land-use change, and forestry. Yet, our simulations reveal that these estimates are wide ranging due to uncertainty associated with pig density, the effects of pigs on soil disturbance, and the impact of soil disturbance on CO_2 emissions (95% PI, 0.30 to 94.09 MMT CO_2).

Continents with the largest land area disturbed by wild pigs are Oceania and North America (Table S2) because the majority of their current non-native geographic range is in these areas (Figure 2). Oceania has considerably higher CO_2 emissions from wild pigs than any other region on average (Table S3), amounting to over 60% of the total emissions from wild pigs (Figure 3). Still, our simulations indicate a wide range of soil disturbance and CO_2 emissions across all continents invaded by wild pigs (Tables S2 and S3). For example, in Oceania the median CO_2 emissions from wild pigs is 2.96 MMT CO_2 per year (equivalent to that of 643,000 passenger vehicles) while the mean is 13.29 MMT CO_2 (the same as nearly three million passenger vehicles). Furthermore, although South America has nearly half of the disturbed land from wild pigs than neighboring North America (Table S2), it has nearly equivalent CO_2 emissions (Table S3; Figure 3) due to considerably higher soil respiration in areas like the Amazon Basin (Raich et al., 2002). Africa and Asia, however, have comparatively less disturbed soil area and CO_2 emissions from wild pigs than other regions (Tables S2 and S3; Figure 3).

4 | DISCUSSION

Although wild pigs contribute to global CO_2 emissions, their soil disturbance also affects food security, economic development, and biodiversity protection (Barrios-Garcia & Ballari, 2012; Risch et al., 2021). While we exclude tillage lands from our analysis to avoid overestimating CO_2 emissions from soil disturbance, wild pigs have been shown to damage important food crops and have indeed been shown to reduce agricultural yields (Barrios-Garcia & Ballari, 2012) amounting to at least $1.5 billion USD annually in losses and control costs alone (Pimental, 2007). Such damages are not only costly from an economic perspective (Diagne et al., 2020), but they may reduce our productive capacity for food consumption. Beyond agriculture, wild pigs have been shown to have dramatic impacts on terrestrial and freshwater ecosystems as they are thought to have played a role in nearly 30% of assessed species being threatened (Gurevitch & Padilla, 2004) and directly threaten 672 species across 54 countries, many of which are already imperiled (Risch et al., 2021). More specifically, wild pigs have been shown to reduce populations of plants through their rooting behavior, consume eggs of and prey on endangered species, facilitate invasive plant spread, and exacerbate emerging infectious diseases (Barrios-Garcia & Ballari, 2012; Risch et al., 2021; Zhou et al., 2018).

There is significant likelihood that wild pigs will expand beyond their current non-native distribution, as highlighted in recent predictions of wild pig densities globally (Lewis et al., 2017; Snow et al., 2017) (see Figure 2 for predicted distribution). The resulting

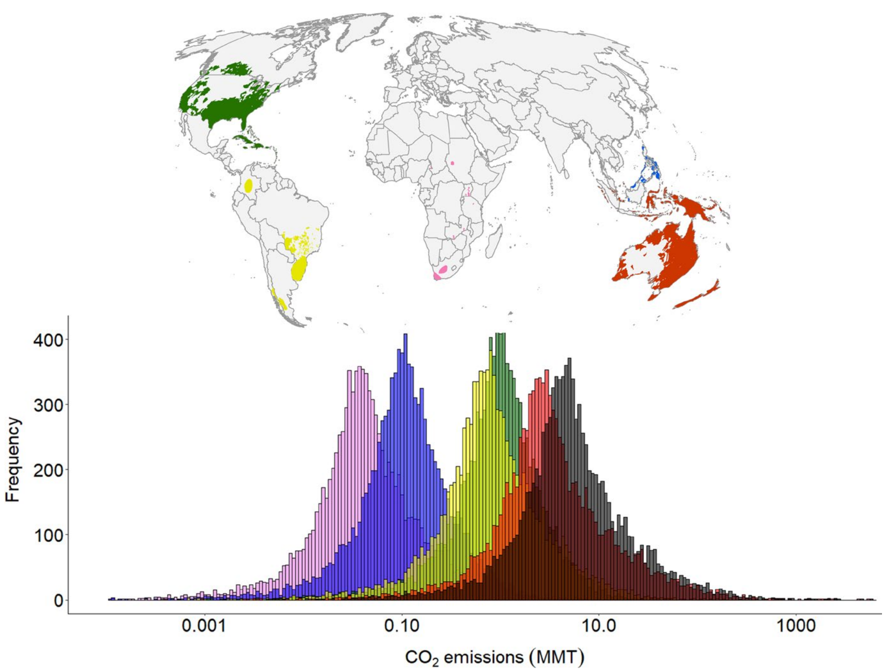

FIGURE 3 Simulations of CO_2 emissions from wild pig (*Sus scrofa*) soil disturbance in their non-native geographic distribution. Histograms of annual CO_2 emissions in million metric tonnes (MMT; log10 scale) from wild pig soil disturbance derived from 10,000 simulations of wild pig density, soil disturbance, and proportion increase of soil CO_2 emissions as a result of wild pig soil damage in their current non-native distribution. The black-shaded histogram represents total results across terrestrial Earth, while the additional colored histograms correspond to individual continents. The colored areas on the map represent the current non-native geographic distribution of wild pigs

soil damage and CO_2 emissions will be more extensive than what has been estimated in this study. While targeted management actions prevent the spread of wild pigs, most mainstream techniques result in CO_2 emissions like the use of vehicles for hunting, baiting, deploying traps, and installing barriers (Davis et al., 2018; Parkes et al., 2010). Although the emissions associated with management are unknown, the long-term benefits of wild pig prevention are substantial. In considering this, one may find that wild pig control costs versus long-term benefits purely in terms of reduced CO_2 emissions may be more cost effective than other strategies even before one considers the collateral benefits to food production and biodiversity protection—an exploration of these trade-offs would be of great value.

A fundamental goal of international environmental agreements is for member countries to combat climate change through the reduction of carbon emissions. We identify that Oceania is the source of over sixty percent of all CO_2 emissions from wild pig soil disturbance yet is less than six percent of global land mass, suggesting opportunities are high in this region for assessing the long-term benefits of their reduction. Furthermore, there is great opportunity for future research to investigate additional climate impacts from wild pigs, such as methane release and the loss of below and above ground carbon from vegetation biomass. We hope this paper stimulates discussion on the role of invasive species for not only contributing to anthropogenic greenhouse gas emissions, but also spurring further research that looks at the local benefits to countries at tackling threats to soil, like invasive species, to reach their sustainable development goals (Bossio et al., 2020; Bradford et al., 2019; Lal, 2004). Such a research direction will bring untapped benefits by reducing emissions and by securing biodiversity and food security into the future.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

C.J.O and N.R.P. formulated the idea of the manuscript. C.J.O. drafted the manuscript and carried out the analyses with V.B.E. with input from N.R.P., J.H., and M.H.H. E.M.M helped frame the study. J.S.L. provided the wild pig density model and assisted with editing the manuscript. All authors assisted with writing and editing the manuscript.

DATA AVAILABILITY STATEMENT

The wild pig density model and associated data for predicting density that informed this analysis can be obtained from Lewis and colleagues (Lewis et al., 2017); the soil respiration data are openly available at https://data.ess-dive.lbl.gov/view/doi:10.3334/CDIAC/LUE.NDP081; the human footprint data are openly available at https://datadryad.org/stash/dataset/doi:10.5061/dryad.052q5; the spatial data for global cropland tillage are openly available at http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:3584892. Datasets generated during and/or analyzed during the current study are available from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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