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RESEARCH ARTICLE

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Loss of loess in the geological record due to poor preservation

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Abstract

Loess deposits are widespread in the Quaternary, but relatively rare in older geological records. This disparity is commonly linked to the unique climate conditions of the Quaternary, but those cannot fully explain the scarcity of loess in older records. Instead, we propose that the poor preservation of loess also plays an essential role. To test this hypothesis, we assess the preservation potential of loess by quantifying its modern-day distribution in active sedimentary basins. This analysis shows that on the global scale only 20% of loess occurs in basins of which the majority is in a foreland setting. This could be due to nearby silt-producing mountains and the effects of rain shadow aridity. The other 80% is ultimately either eroded or reworked and therefore poorly preserved in the long term. This conclusion implies that loess deposits may have been more common in pre-Quaternary periods, despite being less abundant in the geological record.

1 | INTRODUCTION

Loess is a unique sedimentary deposit that provides quasi-continuous climate records and has been intensively studied over the past decades (Fenn & Prud'Homme, 2020; Lehmkuhl et al., 2021; Maher, 2016; Muhs, 2013; Muhs & Bettis, 2003; Pye, 1995; Schaetzl et al., 2018; Sun et al., 2020). It is defined as a terrestrial body of silt-sized clastics formed by the accumulation of windblown dust (Pye, 1995), which is subsequently altered by pedogenic and diagenetic processes (Pécsi, 1990; Sprafke & Obreht, 2016). Vast loess deposits are known from the Quaternary period, covering at least 10% of Earth's total land surface, mostly in the mid-latitude regions of the Northern Hemisphere (Fenn & Prud'Homme, 2020; Li et al., 2020; Pécsi, 1990). In contrast, pre-Quaternary loess deposits—also termed loessites if lithified (Pye, 1995)—are relatively rare (Brookfield & Silvestro, 2010; Meijer et al., 2020; Nichols, 2009; Potter et al., 2005; Wilkins et al., 2018).

Some siltstones have been interpreted as loessites, but often based on ambiguous compositional and textural criteria that are indistinguishable from fluvio-lacustrine deposits resulting in debates on their depositional origin (Meijer et al., 2020). Hence, some well-known examples of loessites such as the Neogene Red Clay in China (An et al., 1999, 2001; Ding et al., 1998; Guo et al., 2002, 2010; Sun et al., 1998) and the Triassic siltstones in northwestern Europe (Jefferson et al., 2002; Mao et al., 2021; Wilkins et al., 2018) have been alternatively interpreted as distal fluvio-lacustrine mudflats, possibly with additional contributions of aeolian dust (Alonso-Zarza et al., 2009, 2010; Li et al., 2019; Meijer et al., 2020; Peng et al., 2012; Talbot et al., 1994). This is supported by recent developments in provenance studies showing that locally eroding bedrock is the main source for the Chinese Red Clay, in contrast to the Quaternary loess which is more distally sourced (Bohm et al., 2022; Liu et al., 2019; Nie et al., 2014; Shang et al., 2016; Zhang et al., 2018). Possible loessites of various ages have been reported in North America (Barendregt et al., 1997; Fan et al., 2020; Soreghan et al., 2008, 2014), South America (Bellosi, 2010; Montalvo et al., 2008) and Europe (Edwards, 1979; Pavelić et al., 2016; Pfeifer et al., 2021). Yet, extensive loess bodies such as those recognized in the Quaternary are rare in older strata. Here, we explore the role of preservation in driving this conspicuous scarcity of loess in the older geological record.

2 | LOESS PRODUCTION AND PRESERVATION MECHANISMS

The formation of extensive loess deposits requires (1) abundant loose, fine-grained material at the source, (2) competent wind systems to transport large quantities of dust and (3) a trapping mechanism such as vegetation, a wetted surface, or a topographic obstacle to accumulate the dust (Lehmkuhl et al., 2021; Muhs, 2013; Muhs & Bettis, 2003; Pye, 1995; Wright et al., 2001; Zheng, 2016). The Quaternary period has been suggested to be especially suitable for the formation of loess because glacial grinding and possibly frost cracking produced vast amounts of silt, which was easily deflated from dry and unvegetated floodplains and continental shelves during glacials (Assallay et al., 1998; Bateman, 2013; Fenn et al., 2022; Herman et al., 2013; Herman & Champagnac, 2016; Lehmkuhl et al., 2021; Li et al., 2020; Mahowald et al., 1999; Muhs & Bettis, 2003; Schaffernicht et al., 2020; Smalley, 1966; Soreghan et al., 2016; Wright, 2001). However, other mechanisms such as abrasion by wind and water, chemical and salt weathering, aggregation of clay minerals and inheritance from fine-grained parent rocks can produce large quantities of silt as well (Fenn et al., 2022; Lancaster, 2020; Muhs & Bettis, 2003; Potter et al., 2005; Wright, 2001, 2007). Especially high-energy transport processes in tectonically active mountains play an important role in producing silt (Assallay et al., 1998; Smalley, 1995). Furthermore, arid and semi-arid regions with loose sediments occurred throughout the geological past and may have been even more abundant during times with supercontinents or moisture-blocking mountain ranges than during Quaternary glacial periods. Thus, the availability of loose silt is unlikely to have inhibited the formation of loess before the Quaternary.

Instead, we propose that the poor long-term preservation of loess is essential in explaining the lack of older loess deposits. Sedimentary basins act as an important source for the formation of loess but not necessarily as a sink (e.g. Smalley et al., 2009). Most loess is derived from windblown reworking of nearby floodplain silts such as from the Danube (Fenn et al., 2022; Jipa, 2014), Po (Costantini et al., 2018), Rhine (Lehmkuhl et al., 2016) and Rhône (Bosq et al., 2018) rivers in Europe, the Mississippi and Missouri rivers in the US (Muhs & Bettis, 2003) and the Yellow River in China (Licht et al., 2016; Nie et al., 2015; Stevens et al., 2013). This dust settles from atmospheric suspension and is subsequently trapped by nearby topography or vegetation to form extensive loess bodies that drape the pre-existing topography (Figure 1; e.g. Bertran et al., 2016; Gild et al., 2018; Lehmkuhl et al., 2016; Mason et al., 1999; Muhs, 2013; Pye, 1987, 1995). Yet, these areas of stable dust accumulation are generally outside of the active sedimentary basins with little to no preservation potential over longer geological timescales. The loess that settles here is ultimately eroded or reworked by aeolian, colluvial and alluvial processes (e.g. Kapp et al., 2015; Lehmkuhl et al., 2016; Van Loon, 2006; Vandenberghe et al., 2018).

Statement of significance

Loess is a windblown deposit of key importance for Quaternary palaeoclimate reconstructions, but relatively rare in pre-Quaternary records. The modern-day distribution of loess shows that the majority accumulates outside of active sedimentary basins due to its windblown nature and is unlikely to be preserved on geological timescales. Thus, the poor preservation potential of loess plays an important but commonly overlooked role in making loess such a uniquely abundant deposit in the Quaternary record.

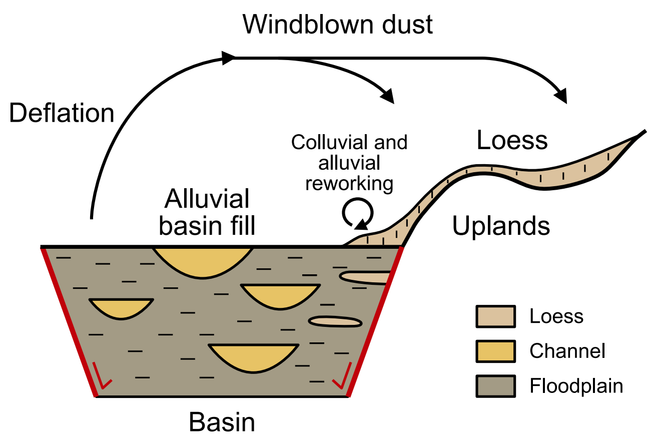

FIGURE 1 Conceptual model of loess deposition and long-term preservation based on figures by Machalett et al. (2006), Pye (1995) and Rits et al. (2016). Deflation of alluvial silt followed by suspension settling of windblown dust results in loess bodies draping the underlying landscape. Over long-term geological timescales, these bodies are reworked by colluvial and alluvial processes before being preserved in geological basins. Note that the vertical dimension is exaggerated. [Colour figure can be viewed at wileyonlinelibrary.com]

Water-laid sediments, on the other hand, accumulate preferentially in basins due to the reduction in slope and the corresponding drop in fluid velocity. Therefore, any loess that does accumulate in basins is likely to be overwhelmed by alluvial processes. Reworking of loess is further facilitated by the loosely packed fabric of loess, which makes it susceptible to collapse and gully erosion, especially after the infiltration of water breaks down the carbonate cements and clay aggregates (Brookfield & Silvestro, 2010; Derbyshire, 2001; Li & Mo, 2019; Nichols, 2009; Pécsi et al., 1990; Pye, 1987). Minor and incidental fluvial activity may already be sufficient to significantly erode primary loess and transform it into an alluvial deposit, adding to the low preservation potential of loess on long timescales. This can be observed in the Quaternary sedimentary record of the Weihe Basin, bordering the southern Chinese Loess Plateau. Here, only few primary loess bodies were identified and the record is instead dominated by fluvio-lacustrine deposits of reworked loess (Rits et al., 2016).

3 | QUANTIFYING LOESS IN SEDIMENTARY BASINS

To estimate the long-term preservation potential of loess, we assess the relative amount of loess deposits found in subsiding basins, which is a prerequisite for registration in the geological record (Nyberg & Howell, 2015; Wang et al., 2018). A renewed interest in the mapping of loess has provided detailed maps of global and regional loess distribution (Fenn & Prud'Homme, 2020; Lehmkuhl et al., 2021; Li et al., 2020). We combine these maps with a high-resolution global map of active sedimentary basins classified by tectonic origin and specifically created to assess biases in the geological record (Nyberg & Howell, 2015; Appendix S1). We first discuss the results from the global yet relatively low-resolution loess map (Fenn & Prud'Homme, 2020 and references therein) and then focus on two well-known loess regions which have been mapped at higher resolution, namely Europe (Lehmkuhl et al., 2020, 2021 and references therein) and China (Li et al., 2020 and references therein).

The global analysis shows that currently 20% of loess is found in basins (Figure 2). Therefore, at least 80% of primary loess is highly unlikely to be preserved in a future geological record.

The proportion of loess in basins is similar to the total land area composed of terrestrial basins (16%; Nyberg & Howell, 2015). This confirms that loess, unlike alluvial deposits, is not depositing preferentially in basins but appears to settle from the atmosphere indiscriminately. The loess that occurs in basins is mostly found in Argentina, in Eastern Europe bordering the Carpathians and the Black Sea, in Central Asian foreland basins, in northeastern China and along the coast of Siberia (Figure 2). However, it should be noted that some of these deposits might be reworked loess, especially in Argentina (Zárate, 2003), the Pannonian Basin of Eastern Europe

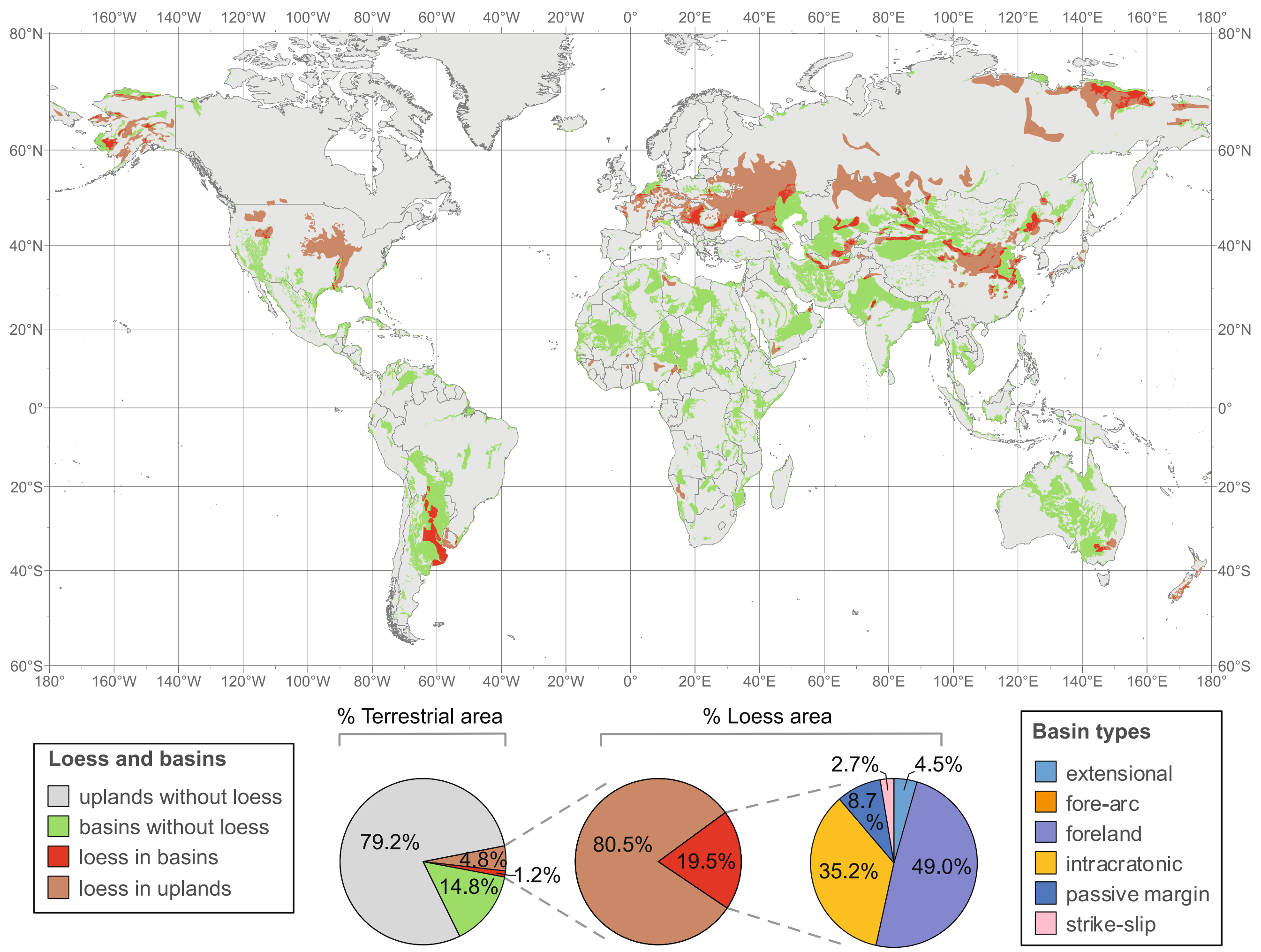

FIGURE 2 Map and pie charts showing the global distribution of terrestrial sedimentary basins (Nyberg & Howell, 2015) and loess deposits (Fenn & Prud'Homme, 2020). Brown colours represent loess not occurring in basins, and red colours represent loess occurring in basins (1% of total land area, 20% of total loess area). Green colours represent remaining basin areas, the rightmost pie chart shows the tectonic origin of the basins that contain loess. Note that the map is plotted in a Gall stereographic projection for visibility of high-latitude regions, but all calculations were carried out in equal-area projections. [Colour figure can be viewed at wileyonlinelibrary.com]

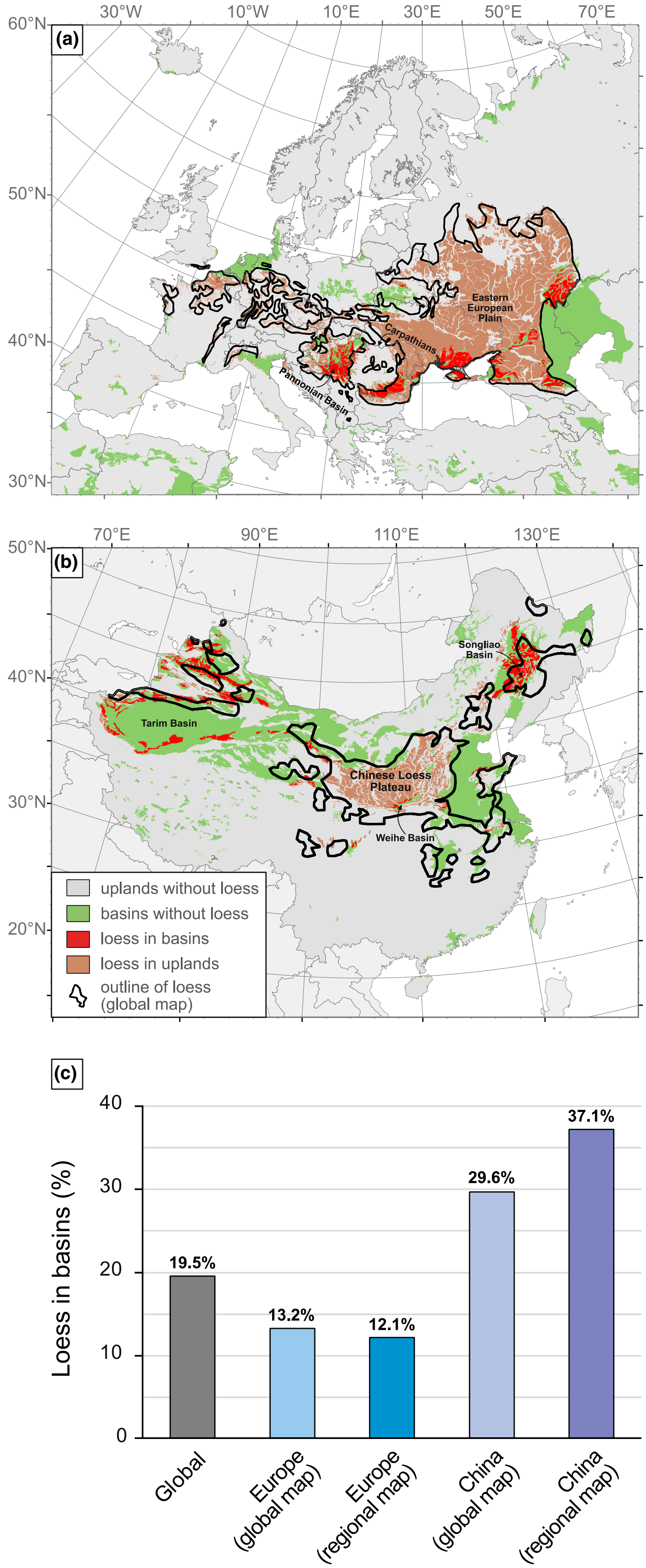

FIGURE 3 Regional maps showing loess and basin distributions at higher resolution, for (a) Europe (Lehmkuhl et al., 2020) and (b) China (Li et al., 2020). The use of colour on the maps is the same as in Figure 2. The thick black lines indicate the loess distribution according to the global map (Fenn & Prud'Homme, 2020), shown for comparison with the regional maps. Both maps are plotted in Lambert conic projections. (c) Percentages of loess in basins using the global and regional maps. [Colour figure can be viewed at wileyonlinelibrary.com]

(Haase et al., 2007) and the Yedoma deposits in Siberia and Alaska (Murton et al., 2015; Strauss et al., 2017). About half of the loess in basins is found in foreland settings, even though these constitute only 10% of the continental basins (Nyberg & Howell, 2015). Foreland basins, therefore, seem to be particularly capable of preserving loess deposits.

Loess occurrence varies regionally as shown by the detailed maps of Europe and China (Figure 3). The loess-in-basin percentage is relatively low in Europe (12%), but higher in China (37%). The percentage derived from the European part of the global map compares very well with the percentage obtained from the regional map of Europe (1% difference), whereas the Chinese part of the global map gives a somewhat lower percentage than the regional map of China (7% difference). This deviation is mostly due to the loess around the Tarim Basin in western China, which is underestimated in the global map. Nevertheless, these detailed analyses for Europe and China show that the lower-resolution global map provides a decent estimate for the total amount of loess in basins and thus for the overall long-term preservation potential.

4 | DISCUSSION

Our study reveals a relative absence of loess in basins, even though 60% of all terrestrial basins occur in arid regions (Nyberg & Howell, 2015), where dust transport is prevalent. Many well-known loess sequences, such as the Chinese Loess Plateau and the Eastern European Plain, are not in basins and therefore actively eroding in the long term (e.g. Kapp et al., 2015). This confirms the conceptual model of loess being deposited predominantly outside of active sedimentary basins which have acted as sources for windblown dust rather than sinks (Figure 1). A few basins, however, are exceptions as they contain extensive areas of primary loess, including the Andean basins of Argentina (Torre et al., 2022; Zárate, 2003), the Danube basins in Europe (Fenn et al., 2022; Jipa, 2014; Marković et al., 2015), the Central Asian basins (Li et al., 2019; Machalett et al., 2006) and the Songliao basin in northeastern China (Li et al., 2020; Wu et al., 2021). These are all foreland basins formed by nearby uplifts, which could have played an important role in providing abundant silt for the formation of loess (Assallay et al., 1998; Fenn et al., 2022; Li et al., 2020; Muhs & Bettis, 2003; Smalley, 1995). Furthermore, these topographies affect atmospheric circulation and may cause aridity due to the rain shadow effect thereby further promoting loess genesis. For example, the Andes block westerly moisture resulting in dry, dust-transporting winds in Argentina (Pullen et al., 2022) and the Tien Shan causes aridity and subsequent loess deposition in western China (Sun, 2002). We thus conclude that the proximity to mountains makes foreland settings more suitable to preserving loess deposits than other basin types. This also indicates that changes in tectonic settings throughout geological history could have either increased or further lowered its preservation potential. It follows that future work aimed at identifying loessites and reconstructing dust fluxes in the deep past should focus on foreland basins.

Finally, we note that the validity of our study is based on the accuracy of the maps and that future improvements in loess mapping might affect our results, especially in the more poorly mapped regions such as Argentina (Zárate, 2007) and Siberia (Strauss et al., 2017). Additional complications arise from debates on the role of in situ pedogenic and diagenetic processes in the classification of loess (Pécsi, 1990; Pye, 1995; Smalley et al., 2011; Sprafke & Obreht, 2016). This has resulted in the use of different loess definitions between countries or even within a country and may cause inaccuracies in the geological and soil maps, especially in the more humid regions where pedogenic processes dominate (Lehmkuhl et al., 2018, 2021; Lindner et al., 2017). Nevertheless, our results show that loess occurs predominantly outside of active sedimentary basins in both the global and detailed maps and we can therefore conclude that the long-term preservation potential is limited. This implies that the geological record is biased against loess, and that windblown dust may have been more abundant in pre-Quaternary periods than commonly thought. Thus, not only the glacial climatic conditions of the Quaternary, but also the preservation bias makes loess so uniquely abundant in recent geological records.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Data preparation and analyses.

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