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Short Communication

Arctic's man-made impervious surfaces expanded by over two-thirds in the 21st century

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The Arctic, located at the northernmost part of the Earth, plays a disproportionately crucial role in regulating global climate and affecting the surface energy balance [1]. Over the past decades, a multitude of environmental changes have been observed in the terrestrial section of the Arctic, including permafrost thawing, land ice retreat, and vegetation greening/browning. These changes not only threat the delicate network of the high-latitude biomes, but also influence human communities far beyond the Arctic limits [2]. Understanding the emergence and consequence of Arctic transitions requires considerations from different aspects. However, compared to the scientific attention on climate effects, the role of anthropogenic activities in affecting the Arctic remains poorly studied [3], despite the potential of their interaction with the climate in complex ways to alter the Arctic ecosystem functions [4].

A representative indicator of human footprint is man-made impervious surface, defined as land covers grouping artificial structures that prevent water filtration into deep soil [5]. The proliferation of man-made impervious surface frontiers into Arctic natural ecosystems alters land physical properties, which contributes to local climate change and—in turn—triggers geological hazards (e.g., thermokarst and flooding) that can cause severe damages to the built-up environment [6]. Moreover, for the next few decades, it is expected to see a continuation of man-made impervious surface growth associated with Arctic resources extraction [7]. Monitoring long-term dynamics of man-made impervious surfaces is thus crucial for projecting polar ecosystem evolution and ensuring sustainable development.

Satellite remote sensing has revolutionized our ability to observe the Earth in a repeated, cost-efficient manner, rendering huge progress made towards the goal of capturing comprehensive information of man-made impervious surface dynamics [8–11]. Notwithstanding recent progress in impervious surface monitoring from space, circumpolar-level remote sensing-based studies have been so far limited by several factors. In the Arctic, the common presence of small-scale man-made impervious surface clusters (e.g., the development of oil/gas deposits) gives rise to "low-magnitude" land surface changes, which may be masked by noise associated with normal temporal variation or other naturally occurring disturbances. In addition, cloud contamination and high solar zenith angles will further induce uncertainties into the results derived from satellite image time series trajectories. To date, a consensus on the Arctic's man-made impervious surface dynamics is still elusive.

To fill this scientific gap, we for the first time created a 20-year long annual Circumpolar Arctic Man-made Impervious surface product (termed CAMI hereafter, 1999–2018) using the full archive of 30 m spatial resolution Landsat data (~160,000 images, Fig. S1 online). A comprehensive framework was designed at the pixel level to identify where the newly built impervious covers were and when the associated land conversions occurred for the entire Arctic landmass (Figs. S2 and S3, Tables S1 and S2 online). Detailed descriptions of materials and methods can be found in Supplementary materials. According to our validation, the CAMI product is reasonably consistent with the reference samples (overall accuracy greater than 85%, temporal bias less than one year, Tables S3 and S4, and Fig. S4 online), and is capable of providing spatiotemporally resolved monitoring results that were not fully captured by other existing land cover or impervious surface datasets (Table S5, Figs. S5 and S6 online). We conducted both sample-based and map-based CAMI area estimates to ensure the reliability of all the statistics reported in this paper (Table S6 online). Observed

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CAMI expansions were further attributed to different anthropogenic activity types (i.e., change agents) including industrial development, human settlement construction, and traffic paving (Tables S7 and S8, Fig. S7 online). We aim, by resolving patterns and drivers of Arctic's man-made impervious surface area growth, to improve our understanding of the human-dominated Earth system dynamics at high latitudes, which could benefit the ongoing climate change mitigation efforts under current and future scenarios.

The Arctic's man-made impervious surface areas showed a rapid, but nonuniform growth (Fig. 1). During the first two decades of the twenty-first century, the total gained area of man-made impervious surface based on the CAMI product is estimated to be 266.2 km^2, equivalent to 68.2% growth relative to the year 1999. We also implemented a bias-adjusted area estimation, which exhibited a consistent magnitude of man-made impervious surface expansion (264.7 ± 5.1 km^2 or 76.4% increase, see Supplementary materials). According to the CAMI map, man-made impervious surface clusters have occupied the most parts of the terrestrial Arctic by the year 2018, but they vary strongly in terms of area and emerge year (Fig. 1a). Of the six Arctic countries involved in this study, Russia leads the expansion of man-made imperviousness. More specifically, the mapped impervious surfaces in Russia exhibited an accelerated increase of 98.1%, an order of magnitude even higher than the global impervious surface growth rate within the study period (i.e., an 81.2% increase, according to Gong et al. [11]). By contrast, impervious surface area gain was relatively limited in the other five countries (Canada, Greenland of Denmark, Iceland, Norway, and the Alaska state of the United States), accounting for less than 30% of the total expanded man-made impervious surface areas in the Arctic. We calculated the annual rate of impervious surface increase at the national level, and again found an obvious discrepancy between Russia and the other countries (Fig. 1b). For Russia, the second decade (2010–2018) exhibited a noteworthier impervious cover growth acceleration than the first decade (1999–2009), whereas the opposite trend was observed in Canadian Arctic, Alaska and Northern Europe. Moreover, man-made impervious surface expansion was unevenly distributed along latitude and longitude gradients (Fig. 1c). The majority of man-made impervious surface gain occurred in Low and Oro Arctic zones (75°N southward), and the eastern Hemisphere presented the majority of the CAMI dynamics, reflecting more pronounced anthropogenic activities in Eurasia than in North America during the early twenty-first century.

Some notable man-made impervious surface clusters in the Arctic have been previously documented by local- or regional-level studies [4,12]. Our CAMI estimates match well with those records, meanwhile providing the pixel-specific identification of the change year from non-impervious to impervious surfaces (Fig. 1d–h). Such information is essential for comprehensively understanding the complex impacts of anthropogenic activities within polar ecozones influenced by political, social and economic factors [13]. For example, we observed spatially stable CAMI patterns for two resource-based towns in Russia: Vorkuta located in the Pechora coal basin (Fig. 1d) and Yamburg located on the Gulf of Ob (Fig. 1e), indicating limited human settlement encroachment within these two regions since the twenty-first century. By contrast, in Sabetta, a harbor on Yamal Peninsula, Russia (Fig. 1f), spatially contiguous hotspots of man-made impervious surface gain were commonly found after the year 2010, primarily attributed to the construction of gas field infrastructures and associated traffic pavements. Consistent with a previous study [4], the majority of impervious surface areas in Prudhoe Bay oil field, Alaska, the United States (Fig. 1g) was built prior the year 2000, despite the existence of scant industrial and traffic developments during the study period. Our satellite-derived CAMI product also captured the full development process of the well-known Diavik Diamond Mine, located in the Northwest Territories, Canada (Fig. 1h). In particular, initial open pit mining operations and associated traffic paving started at the year 2001, followed by a relatively stable period due primarily to the transition to underground mining operations. After the year 2015, however, new exploration activities were again detected, especially in the north and west regions.

The drivers of man-made impervious cover expansion vary substantially over space and through time (Fig. 2). In general, an estimated 54% of the detected CAMI expansions are associated with industrial development and 42% with traffic paving (Fig. 2a), reflecting the prominent role played by these two land use activities in driving man-made impervious surface growth in the Arctic [14,15]. At the national level, our mapping results show that industrial development accounts for the majority of observed CAMI expansions in Canada (74%) and Russia (50%). By contrast, traffic paving is more frequently detected in Alaska (73%) and Nordic countries (54%). Additionally, Northern Europe is the only statistical unit with over 10% of man-made impervious surface area growth contributed by human settlement construction. Temporally, industrial development and traffic paving always exceed human settlement construction in terms of annual CAMI expanding area, although their area ratios display a strong variability (Fig. 2b). The temporal diversity of land use activities' impact on CAMI change is also observed at the national level. For example, in Canadian Arctic, industrial development contributes the largest shares to man-made imperviousness growth in 13 out of the 19 years. But in Nordic countries, CAMI expansion contains greater proportions from human settlement construction and traffic paving, ranging from 44% to 100% throughout the past two decades. In agreement with the Pan-Arctic pattern, activities related to human settlement construction are very rare in Russia, only accounting for less than 20% of the detected changes in all years. This result mirrors the joint impact of the other two land use types on impervious cover expansion over the Far North of Russia. In Alaska, however, changes are mainly caused by traffic paving, except for the year 2014 when industrial development activities had a more outstanding contribution percentage.

In summary, our results provide satellite-derived evidence of unprecedented man-made impervious surface expansion across the Arctic landmass. This finding is in contrast to those in previous studies that mainly concentrated on areas at low/middle latitudes, and therefore gives unique insights into global environmental change caused by anthropogenic activities. Our estimates suggest that Russia has become a world leader in Arctic's new imperviousness encroachment, with industrial development and traffic paving identified as primary drivers. As a millstone following this pilot study, the improved version of the CAMI dataset at 10 m resolution is currently under development, and will be publicly available as a part of the "GEOARC-2021" report by the Global Ecosystem and Environment Observation Analysis Research Cooperation. We anticipate that the continuing endeavor of CAMI development can enlighten innovative Arctic management by public and non-governmental sectors. The CAMI dataset is publicly available from Science Data Bank (https://www.scidb.cn/).

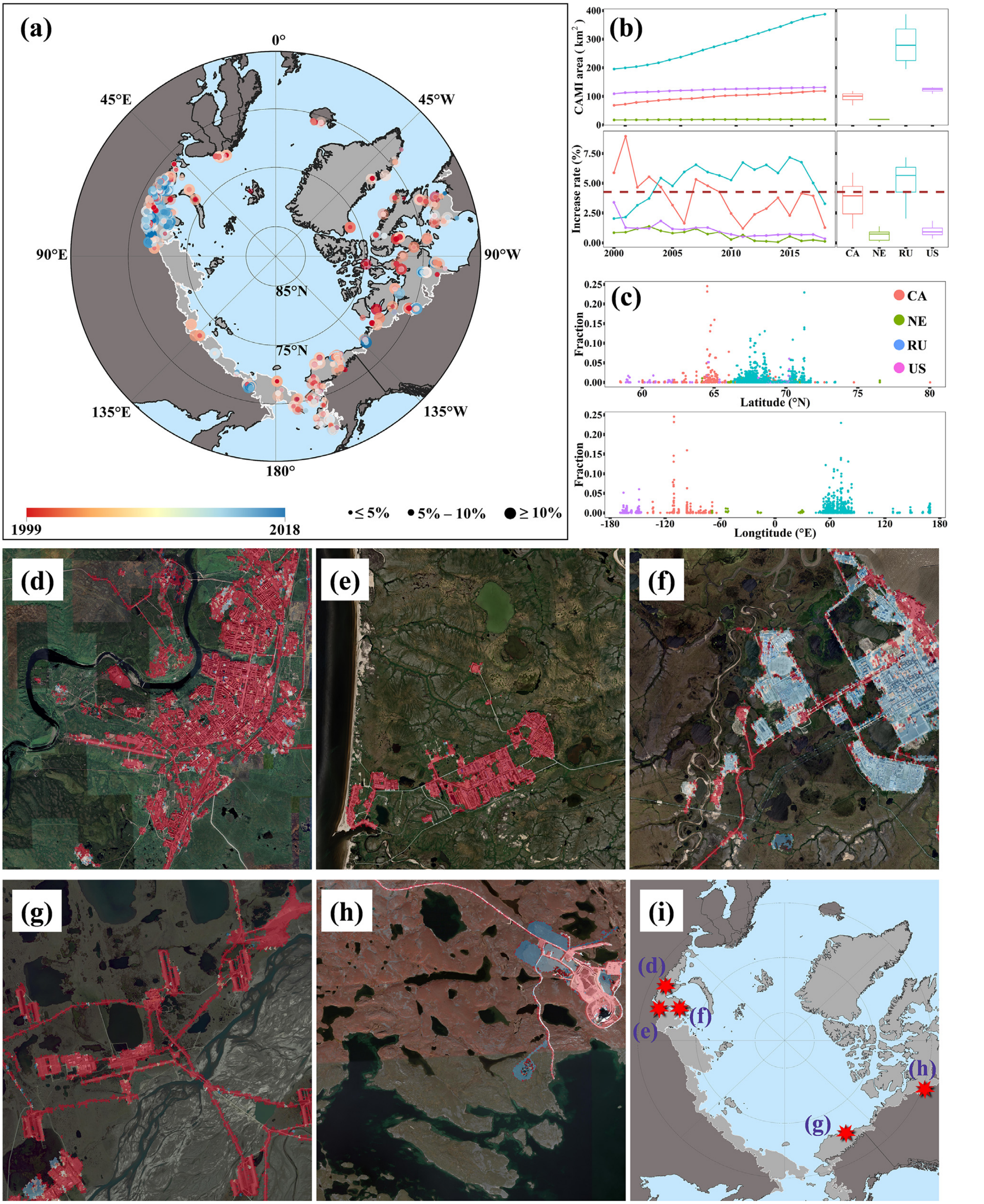

Fig. 1. CAMI estimates of man-made impervious surface expansion from 1999 to 2018. (a) Distribution of man-made impervious surface areas throughout the terrestrial Arctic. Each circle in the map represents the mean estimates of emerging year (color scale) and fractional percent of man-made impervious surface area (size scale) at a 1 km × 1 km resolution. (b) Annual CAMI growth at the national level. CA, NE, RU, and US represent Canada, Northern Europe (Greenland, Iceland, and Norway), Russia, and the United States (Alaska), respectively. The dashed brown line shows the average annual growth rate of global impervious surfaces from 1999 to 2018 according to Gong et al. [11]. (c) Latitudinal and longitudinal profiles of CAMI gain during the study period. Fractional area statistics were calculated for every 0.05°. (d)–(h) Further offer zoom-in CAMI mapping results of five typical regions including: Vorkuta, a coal-mining town located in the Pechora coal basin, Russia (centered at 67.5°N, 64.1°E); Yamburg, a gas filed associated human settlement in Nadymsky District, Russia (centered at 67.9°N, 74.9°E); Sabetta, a port with liquefied natural gas plant on the Yamal Peninsula, Russia (centered at 71.2°N, 72.1°E); Prudhoe Bay oil field in northern Alaska, the Unitied States (centered at 70.3°N,148.7°W); Diavik Diamond Mine located in the Northwest Territories, Canada (centered at 64.6°N,110.2°W). (i) Displays geographical positions of (d)–(h).

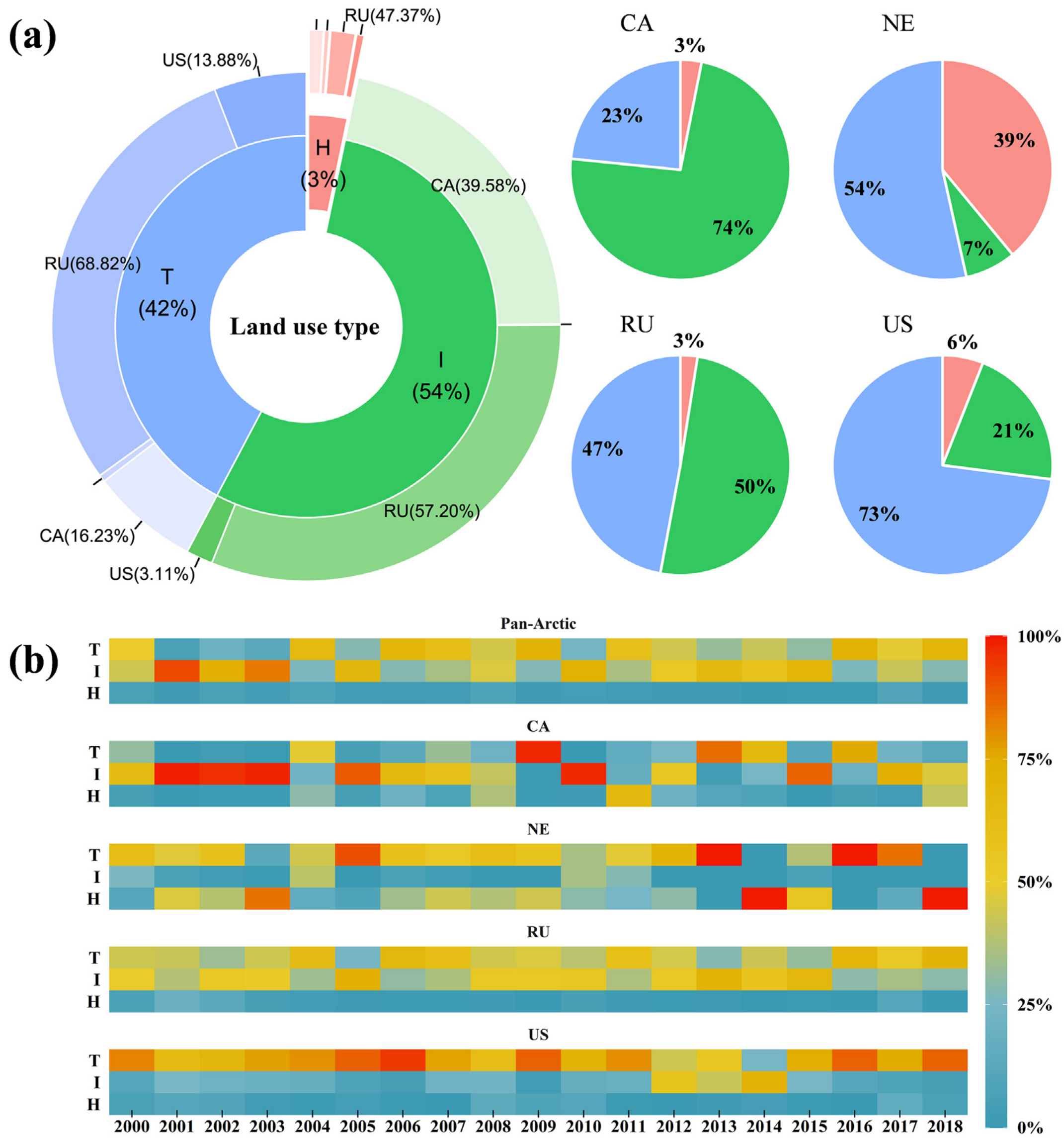

Fig. 2. Quantitative contributions of different land use types to Arctic's man-made impervious surface expansion during the study period. (a) Nation-specific distribution of CAMI growth attributed to three land uses: H (human settlement construction), I (industrial development), and T (traffic paving). Note that less than 1% contributions are not displayed. See Fig. 1 for description of country abbreviations. (b) Annual proportion of CAMI area increase driven by H, I, and T, respectively.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Chong Liu and Xiao Cheng designed the research. Chong Liu and Huabing Huang carried out data analysis. Qi Zhang, Xuanzhu Chen, Xiaoqing Xu and Hanzeyu conducted accuracy assessment. All authors wrote the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2022.06.001.

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