1. Permafrost Region and Permafrost Area

Permafrost is defined as ground (soil or rock and any ice and organic material inclusions) that remains at or below 0°C for two consecutive years or longer (Van Everdingen, 2005). The role of permafrost in affecting the global carbon cycle, natural hazards, and infrastructure is being increasingly acknowledged (Pörtner et al., 2019). This has resulted in an increase in the number of publications reporting or building upon how much of the Earth’s surface is underlain by permafrost (Table S1).

Permafrost presence can vary at a scale of tens of meters due to heterogeneous snow cover, vegetation, terrain, hydrology, and soil properties (Brown, Roger, et al., 1973; Gisnås et al., 2014; Gubler et al., 2011; Smith, 1975). Permafrost distribution has therefore been traditionally conceptualized in terms of permafrost zones that describe the fraction of ground underlain by permafrost. In permafrost zones, where the proportion of ground underlain by permafrost is small (sporadic permafrost or isolated patches), are areas where permafrost is present only in the most favorable conditions, for example where snow cover is thin or in peatlands.

Although the range of areas underlain by permafrost for each zone varies between the studies (Heginbottom et al., 2012), they are most frequently defined as continuous (90%–100%), discontinuous (50%–90%), sporadic (10%–50%), and isolated patches (10% or less) (Brown et al., 1997) (Figure 1). As such, permafrost zones are useful for cartographic displays because they aggregate fine-scale binary data to coarse scales. Early permafrost mapping attempts at local and national scales have already followed this zonation concept (Ferrians, 1965), which has also been adopted by recent permafrost modeling efforts (Gruber, 2012; Obu, Westermann, Bartsch, et al., 2019).
The term *permafrost region* was introduced to describe and quantify the area covered by permafrost zones (Zhang et al., 2000). Because permafrost only underlies a certain percentage of permafrost zones and consequentially the permafrost region, the area actually underlain by permafrost is substantially smaller than the extent of the permafrost region (Heginbottom et al., 2012). The term *permafrost area* is used to describe the area actually underlain by permafrost. For this reason, permafrost area in the Northern Hemisphere occupies about 6 million km² less than the permafrost region, a difference in size equaling three times the area of Greenland or half of the Antarctic continent.

The Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997), compiled by the International Permafrost Association, was created by combining regional maps and expert knowledge on permafrost zones. It provided the first large-scale estimate of the area underlain by permafrost and has been the most commonly used reference regarding the extent of permafrost during the last two decades. Zhang et al. (1999) calculated statistics using this map and reported that “Permafrost underlies about 22.79 × 10⁶ km² or 23.9% of the exposed land surface area in the Northern Hemisphere.” The same authors Zhang et al. (2000) elaborated on the terminology used in Zhang et al. (1999) and explained that the previously published numbers referred to the sum of the area of all permafrost zones (that they termed the permafrost region) and the actual area underlain by permafrost is only 12.21 to 16.98 × 10⁶ km², or from 12.8% to 17.8% of the exposed land area.

Despite this clarification, a substantial number of publications use the permafrost region as a synonym for the area of how much of the Earth’s surface is underlain by permafrost. Within the literature, it is still most commonly stated that about 25% of the Northern Hemisphere, or 17% of the Earth’s surface is underlain by permafrost (Tables S1, S2, and S3). The persistence of citing the incorrect number is shown by the fact that according to Crossref (as of December 2020) 58% out of 33 papers that report permafrost area by citing the clarification by Zhang et al. (2000) still incorrectly used the value of permafrost region (Table S1). The confusion is even greater in interpreting the modeling results of Gruber (2012) and Obu, Westermann, Bartsch, et al. (2019), which reported both permafrost area and region. According to the Web Of Science (as of December 2020) 46 publications referred to the permafrost area from these modeling results but 83% reported the too large values of the permafrost region (Tables S2 and S3).
Studies listed in Tables S1, S2, and S3 most frequently state the area underlain by permafrost in their introductions, causing consolidation of the general opinion that one quarter of the Northern Hemisphere is underlain by permafrost. These numbers are consequentially used in policy documents, such as the United Nation Environment Program report (Schaefer et al., 2012). Also, circumpolar permafrost carbon-stock estimates are often summed up using the extent of the permafrost region (Hugelius et al., 2014; Tarnocai et al., 2009) rather than permafrost area. As such, knowledge of the difference between permafrost area and permafrost region is required to correctly interpret the results of these studies.

The use of incorrect permafrost area estimates can also have an important impact on published scientific results. A recent example is a study by Wang et al. (2020), which compared the permafrost area of the Tibetan Plateau to the permafrost region of the Northern Hemisphere for calculations regarding the amount of thawed soil organic carbon. Similarly, Bosch et al. (2017) used the area of the permafrost region to place potential CO2 emissions from permafrost soils in the context of similar studies. Such examples emphasize the need for clarification regarding the difference between permafrost area and permafrost region, as well as a synthesis of updated permafrost area estimates.

This commentary aims to inform the geoscientific community and general public about the actual area underlain by permafrost and the reasons leading to the overstatements of that area by highlighting the known differences between the permafrost region and permafrost area. This study also provides estimates of spatial permafrost extent for different parts of the globe by summarizing the recent estimates by Aalto et al. (2018), Gruber (2012), Obu, Westermann, Bartsch, et al. (2019), and Zhang et al. (2000).

### 2. Permafrost Area Estimates

Recent permafrost modeling efforts have estimated new permafrost area and/or permafrost region extents for different parts of the globe. Gruber (2012) used a permafrost zonation index to model the distribution of permafrost zones for the 1961–1990 period. He reported a permafrost area that was recalculated from the extent of permafrost zones using the coverage ranges of permafrost zones. The permafrost area was estimated to be between 12.9 and 17.7 × 10^6 km², which accounts for 13%–18% of the exposed land surface area in the Northern Hemisphere. Aalto et al. (2018) used statistical modeling to estimate the circum-Arctic mean annual ground temperatures at zero annual amplitude (2000–2014 period) and reported a permafrost area of 15.1 ± 2.8 × 10^6 km² or 15.8 ± 2.9% of the exposed land surface area in the Northern Hemisphere. In the most recent modeling effort, Obu, Westermann, Bartsch, et al. (2019) used the TTOP equilibrium model to estimate near-surface permafrost temperatures, probability of permafrost occurrence, and permafrost zones for the 2000–2016 period. They reported a mean permafrost area derived from ensemble-run statistics to be 13.9 × 10^6 km² or 14.7% of the exposed land surface in the Northern Hemisphere.

All four studies (Aalto et al., 2018; Gruber, 2012; Obu, Westermann, Bartsch, et al. (2019); Zhang et al., 2000) estimated permafrost area, with the middle of the range calculated Gruber (2012) and Zhang et al. (2000) to be between 14 and 15 × 10^6 km² (with uncertainty ranges up to 3 × 10^6 km²), which equates to 15% ± 3% of the exposed land surface area in the Northern Hemisphere (Table 1). These permafrost area estimates show remarkable agreement despite the different methodologies and calibration data that they used. Nevertheless,
permafrost modeling and permafrost area estimates are subject to uncertainties, which requires that the reported permafrost area numbers are still regarded with accompanying confidence intervals.

Permafrost in the Southern Hemisphere north of 60° is prevalent across the Andes, although it is also likely to be present on Kilimanjaro, in the Southern Alps of New Zealand, and on sub-Antarctic Islands (Obu, Westermann, Kääb, et al., 2019, Obu et al., 2020). The area underlain by permafrost in the Southern Hemisphere is estimated to be between 0.02 and 0.03 \times 10^6 \text{ km}^2 or between 0.05% and 0.08% of the exposed land area. Permafrost modeling suggests that 100% of the Antarctic ice-free areas are underlain by permafrost (Gruber, 2012; Obu et al., 2020) although field studies show that some coastal areas in the South Shetland Islands are not underlain by continuous permafrost (Vieira et al., 2010).

Globally, permafrost underlies between 14 and 15.7 \times 10^6 \text{ km}^2 of the exposed land area (Gruber, 2012; Obu et al., 2020) although field studies show that some coastal areas in the South Shetland Islands are not underlain by continuous permafrost (Vieira et al., 2010). Thus, the permafrost area including Circum-Arctic subsea permafrost can be estimated to be around 17 \times 10^6 \text{ km}^2.

3. Conclusions

The spatial extent of permafrost is frequently overstated within the literature due to confusion between the terms “permafrost region” and “permafrost area.” While the concept of permafrost region is useful for cartographic purposes, studying soil properties, plant ecology, hydrological pathways, and in civil engineering, permafrost area should be used for quantifying the area (km²) underlain by permafrost. Permafrost underlies between 14 and 16 \times 10^6 \text{ km}^2 of the Earth’s exposed land surface, which is around 15% of the exposed land surface in the Northern Hemisphere and 11% of the global surface.

Data Availability Statement

Permafrost extent and temperature data for Andes, New Zealand, and Africa are available through Obu, Westermann, Kääb, et al. (2019).

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