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Editors Opinion

New uses for old tools: Reviving Holdridge Life Zones in soil carbon persistence research

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Take-Home Message

Growing evidence suggests that climate classification facilitates the identification of zones that either agree or disagree with processes explaining soil organic carbon (SOC) persistence. Already forty years ago, *Post* et al. (1982) posited that the strict temperature and precipitation-based classification defining the Holdridge Life Zones (HLZ) provides a descriptive tool to guide our understanding of the heterogeneous distribution of global SOC stocks. Here we argue that this classification has the potential for describing SOC persistence by linking top-down and bottom-up approaches from different scales, which allows selection of individual regional relevancies necessary to manage and track the fate of our largest terrestrial carbon (C) reservoir.

Key words: carbon management / climate classification / global carbon distribution / soil organic carbon persistences

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1 The old tool and the new challenge

Almost 40 years ago, *Post* et al. (1982) introduced how helpful the Holdridge Life Zones (HLZ) classification is in explaining and describing the regional differentiation of soil organic carbon (SOC) stocks on a global scale. They argued it to be "important to establish the relationships between the geographical distribution of SOC and climate as a basis for assessing the influence of changes" suggesting that the geographical location, in terms of climate, influences the SOC distribution. Given the importance of SOC persistence (*Schmidt* et al., 2011; *Lehmann* et al., 2020), in addition to the urgent need to better understand SOC dynamics for climate change mitigation (*Lal*, 2004; *Bradford* et al., 2016; *Amelung* et al., 2020), descriptive tools are needed to guide our understanding of the genesis of SOC stocks and the development of the quantitatively most relevant C stocks. Accordingly, classification by climate zone is experiencing a sort of renaissance within the debate of most relevant mechanisms governing C persistence in space and time. For example, *Rasmussen* et al. (2018) demonstrated that the relative importance of individual SOC stabilization mechanisms scales with climate. *Kramer* and *Chadwick* (2018) revealed how mean annual precipitation (MAP) and potential evapotranspiration (PET) drive reactive mineral retention of SOC, which is particularly fascinating that a non-climate control is influenced by climate variables. This has recently been extended by *Hein* et al. (2020), who showed that hydroclimate explains tropical SOC persistence. Similarly, *von Fromm* et al. (2020) pointed to the ratio of the annual PET to the MAP as the best predictor for SOC distribution. The mean age of SOC also relates to global climate (*Shi* et al., 2020). At the same time, *Hall* et al. (2020) provided climate-related predictors that explain ninety percent of the SOC composition variance. Hence, even at the molecular scale, SOC variability is determined by larger-scaled environmental variables.

To contribute to and advance the present discussion, we revisited and updated the approach of *Post* et al. (1982) by integrating the latest available data on world soil C stocks (*Wieder* et al., 2014) and linking it to the available and updated HLZ classification (*Leemans*, 1990). The idea here was to assess the HLZ classification system as a descriptive tool to explore the ties between climate and SOC persistence. Therefore, we hypothesized that the HLZ classification is able to predict the global SOC distribution, and tested if the prior findings still prove correct for the extended 38 HLZ. We are convinced that this linkage allows (1) to quantitively identify global zones that are most important and susceptible regarding their SOC stocks and (2) to qualitatively distinguish global zones that differ in their processes promoting SOC persistence. To test for process-oriented variabilities across HLZ, we correlated data from the International Soil Radiocarbon Database 1.0 (*Lawrence* et al., 2019) to exemplarily show that the radiocarbon age (^{14}C) supports the predictions of SOC persistence revealed from HLZ classification. We emphasize the need to link SOC dynamics from the process scale (providing the mechanistic understanding of SOC stabilization) to the scales at which decisions are made (using modeling and/or classification approaches) (*O'Rourke* et al.,

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2015; *Lehmann* et al., 2020) and propose the HLZ classification as an effective and descriptive tool to guide research questions leading to a better understanding of climate soil feedback mechanisms.

2 Approach

Post et al. (1982) used 2,696 profiles compiled to 22 Holdridge Life Zones—nowadays we can make use of 8,205 soil profiles spread across all 38 HLZ. The HLZ are defined by biotemperature, MAP and supported by PET (*Holdridge*, 1947), and usually depicted in triangles with humidity on the bottom, biotemperature on the right, and the ratio of PET to MAP on the left axis. The biotemperature is defined as mean annual temperature, calculated after setting all temperatures below 0°C and above 30°C to 0. Potential evapotranspiration is the amount of water that would evapotranspire under optimal soil moisture and plant cover conditions at a given biotemperature and other boundary conditions like wind speed. Holdridge simplified this by using the factor of 58.93 times the biotemperature. When MAP exceeds PET, this ratio is < 1 and the zone is considered as humid; when this ratio is > 1, the zone is considered as dry. The number of humidity provinces increases with biotemperature. The relationships between SOC stocks and biotemperature or humidity (ratio of PET to MAP), respectively are even more apparent when zones are compiled to larger-scaled biotemperature (latitudinal / altitudinal) zones and humidity provinces comparable to the IPCC climatic regions (*Scharlemann* et al., 2014). We assigned the driest HLZ (#1, 7, 12, 18, 25, 32) to the desert zone, the second driest HLZ (# 2, 8, 13, 19, 20, 26, 17, 33, 34) to the dry/steppe zone, the medium humid HLZ (# 3, 4, 9, 14, 15, 21, 28, 35) to the dry/forest zone, the second wettest HLZ (#5, 10, 16, 22, 23, 29, 30, 36,37) to the wet/moist zone, and the wettest HLZ (# 6, 11, 17, 24, 31, 28) to the rain zone.

The HLZ dataset (*Leemans*, 1990) is supplied by the International Institute for Applied Systems Analyses (IIASA) in Laxenburg, Austria, and was retrieved from the FAO GeoNetwork, where it is regularly updated (last update FAO, 2008). The SOC stocks are available from the Regridded Harmonized World Soil Database v1.2 (RHWSD) (*Wieder* et al., 2014) and retrieved online from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. Profile data, the basis of the RHWSD is available online as the database WISE3 (*Batjes*, 2008) on ISRIC–World Soil Information Wageningen University & Research in Wageningen, The Netherlands. Radiocarbon age data were accessed and extracted from the International Soil Radiocarbon Database version 1.0 (*Lawrence* et al., 2019). As a first step, the HLZ dataset was merged with the SOC data by overlaying the HLZ map with the SOC stock map using ArcGIS Pro (version 2.7, ESRI 2020) employing the spatial join function. In a second step, we merged the final product from step one with radiocarbon age data. Means ± standard deviation (SD) and median values of SOC stocks (0–100 cm) and C ages (0–30 cm) were calculated for each HLZ separately. using the statistical software R (version R 3.6.3; *R Core Team*, 2020). The coordinates of the profiles from the WISE3 database were transferred to ArcGIS Pro and allocated to the distribution of the HLZ.

It is of utmost importance to demonstrate at which points the HLZ classification outcompetes other classification systems. Therefore, we used our dataset and tested it for the Global Agroecozones (GAEZ) and the Köppen–Geiger classification. However, the results with these classifications were less clear regarding the prediction of the global SOC distribution (unpublished data). Still, this should be tested more thoroughly, and we appreciate advancements in harmonizing existing systems.

3 Carbon stocks in the Holdridge Life Zones

In line with early findings of *Post* et al. (1982), SOC stocks increased with increasing humidity, and stocks showed trends to decrease with increasing temperature across all levels of precipitation (Fig. 1). The HLZ (top 10%) having highest mean ± SD SOC stocks (Tab. 1) were: #10 boreal wet forest (18.6 ± 15.0 kg m^{-2}), #9 boreal moist forest (17.4 ± 13.8 kg m^{-2}), #17 cool temperate rain forest (17.2 ± 11.8 kg m^{-2}), and #4 polar moist tundra (15.4 ± 10.3 kg m^{-2}). Compared with *Post* et al.

Table 1: Holdridge Life Zones summary of SOC data for the first meter of soil.

HLZ code	HLZ name	HLZ area	Number of samples	Density of profiles	Mean SOC stock	Standard deviation	HLZ soil carbon stock
#		**km^2 10^6**	**Profiles**	**per km^2 10^6**	**kg m^{-2}**		**Pg (10^{12} kg)**
Polar		**10.5**	**55**	**5.3**	**10.1**	**5.6**	**105.6**
1	Ice	0.5	1	1.5	9.6	1.3	6.6
2	Desert	9.8	54	5.5	10.1	5.8	99.1
Subpolar		**9.4**	**66**	**7.0**	**14.4**	**10.5**	**134.1**
3	Dry tundra	0.5	6	12.2	12.9	7.9	6.3
4	Moist tundra	2.5	24	9.5	15.4	10.3	38.7
5	Wet tundra	4.7	21	4.5	14.3	11.2	66.5
6	Rain tundra	1.7	15	8.7	13.1	9.0	22.5

Table 1. Continued.

HLZ code	HLZ name	HLZ area	Number of samples	Density of profiles	Mean SOC stock	Standard deviation	HLZ soil carbon stock
#		**km^2 10^6**	**Profiles**	**per km^2 10^6**	**kg m^{-2}**		**Pg (10^{12} kg)**
Boreal		**17.3**	**259**	**15.0**	**16.5**	**13.6**	**285.3**
7	Desert	0.4	5	12.1	10.3	8.9	4.3
8	Dry bush	1.9	26	13.8	9.6	7.1	18.1
9	Moist forest	9.7	113	11.6	17.4	13.8	168.8
10	Wet forest	4.4	83	18.8	18.6	15.0	82.0
11	Rain Forest	0.9	32	35.2	13.3	9.6	12.1
Cool temperate		**21.3**	**1546**	**72.5**	**9.9**	**7.2**	**211.0**
12	Desert	1.5	32	21.3	4.4	2.8	6.6
13	Desert bush	2.5	77	30.6	5.7	2.9	14.2
14	Steppe	7.4	386	52.3	9.4	4.7	69.3
15	Moist forest	8.2	903	110.0	11.8	8.7	96.8
16	Wet Forest	1.5	141	95.3	13.4	7.5	19.8
17	Rain Forest	0.3	7	28.5	17.2	11.8	4.2
Warm temperate		**11.3**	**825**	**73.4**	**8.0**	**6.2**	**90.8**
18	Desert	0.7	32	47.2	3.7	2.6	2.5
19	Desert bush	1.8	64	35.2	4.8	3.2	8.7
20	Thorn steppe	2.3	100	43.8	6.4	3.7	14.6
21	Dry forest	3.3	297	90.0	8.8	7.3	29.1
22	Moist forest	2.9	296	101.3	11.1	6.1	32.5
23	Wet forest	0.2	28	137.2	14.1	7.6	2.9
24	Rain forest	0.0	8	189.5	12.5	5.4	0.5
Subtropical		**43.5**	**3459**	**79.6**	**7.8**	**5.5**	**340.5**
25	Desert	7.4	83	11.2	4.6	2.4	33.9
26	Desert bush	5.4	156	28.9	5.9	4.3	32.1
27	Thorn steppe	4.4	785	179.0	6.1	4.7	26.9
28	Dry forest	8.2	954	116.1	8.4	5.5	68.6
29	Moist forest	15.1	1227	81.3	9.6	6.1	145.4
30	Wet forest	2.8	249	87.7	11.3	5.6	32.2
31	Rain forest	0.1	5	39.8	11.1	5.8	1.4
Tropical		**22.8**	**1995**	**87.7**	**7.9**	**5.8**	**177.8**
32	Desert	3.9	59	15.0	4.0	1.3	15.7
33	Desert bush	1.6	89	56.5	4.2	1.6	6.6
34	Thorn steppe	1.9	42	22.1	5.2	2.3	9.9
35	Very dry forest	3.3	655	200.7	7.1	3.7	23.3
36	Dry forest	6.6	646	97.7	8.8	6.0	58.2
37	Moist forest	5.3	482	91.8	11.7	7.3	61.3
38	Wet forest	0.2	22	99.6	12.9	8.4	2.9
Sum		**136.0**	**8205**	**60.3**	**9.9**	**54.4**	**1345.1**

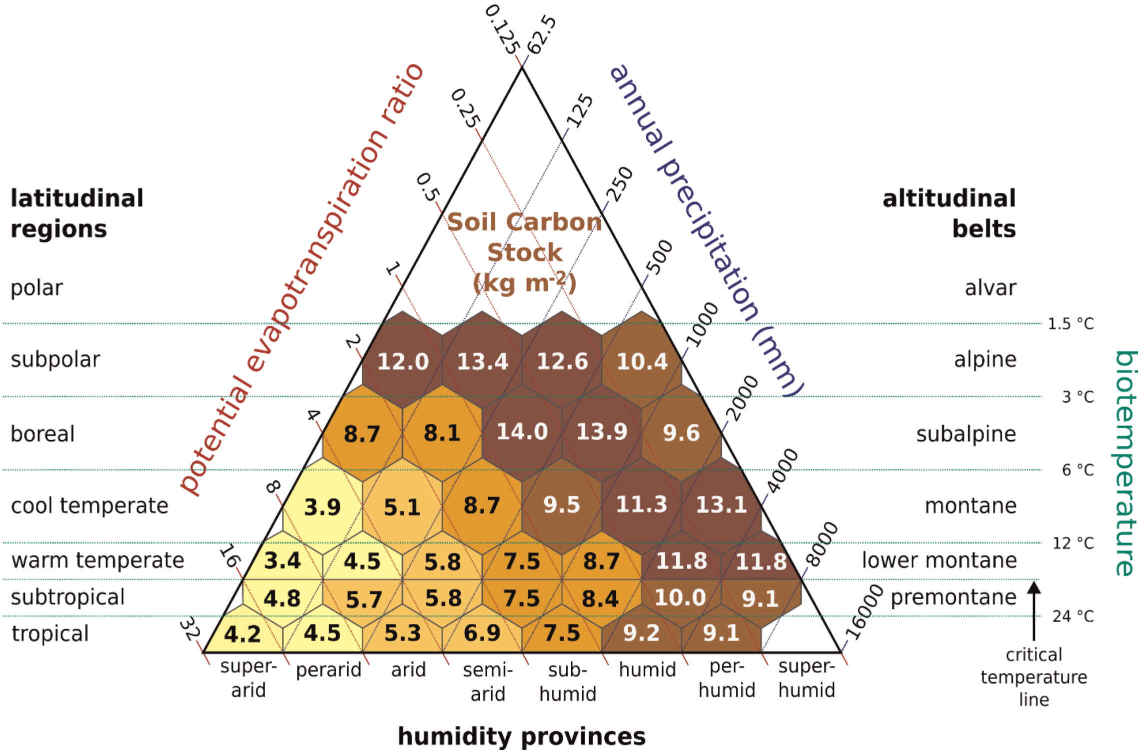

Figure 1: Median SOC stocks (0–100 cm) plotted across the Holdridge scheme for world life-zone classification. Values of biotemperature and precipitation uniquely determine the Holdridge Life Zones (HLZ) and its associated vegetation. Colors represent 5 classes from low SOC stocks (yellow) to high SOC stocks (brown). The format of the figure is based on the HLZ classification scheme digitally created by Peter Halasz (2007): Holdridge Life Zone Classification scheme. Date: 2007-03-03 (https://commons.wikimedia.org/wiki/File:Lifezones_Pengo.svg).

(1982), our analysis was more precise in postulating that the seasonal precipitation pattern of the humid subtropical (#29 subtropical moist forest) and humid warm temperate (#20 warm temperate moist forest) zone would not lead to distinctively lower SOC stocks. Therefore, it seems advantageous to unravel similarities and differences in mechanisms affecting SOC persistence in areas experiencing seasonal precipitation patterns rather than homogenous precipitation. This is particularly important in light of climate change predicting greater heterogeneity in precipitation patterns.

4 Beyond climate control of SOC stocks

From the perspective of soil scientists, the control of SOC persistence beyond the dominant role of climate has always been key to understanding soil function with clay having a profound impact. However, edaphic factors like pedogenic Fe and Al and other mineral associations are increasingly recognized to additionally control for C persistence even at the global scale (*Kramer* and *Chadwick*, 2018; *Rasmussen* et al., 2018). These relations decisively increase our understanding of general patterns contributing to stabilizing C in the soil at scales relevant for C management. By definition, the HLZ classification cannot go beyond climate control, but the latest literature (*Kramer* and *Chadwick*, 2018; *Rasmussen* et al., 2018; *Hein* et al., 2020; *von Fromm* et al., 2020) indicates that multiple controls on SOC persistence vary systematically with climate. HLZ is a good fit to separate SOC stocks into clearly distinguishable and process-oriented zones, varying in their mechanisms to mediate SOC persistence. An indicator of the sensible use of HLZ to approach different regional regimes of SOC persistence processes is the radiocarbon age of SOC. Older SOC ages are the result of longer mean residence times, which hint towards reduced decomposition or increased SOC persistence. The younger radiocarbon age predicts that more freshly produced SOC is included (*Shi* et al., 2020). Under constant production rates, one would assume that the organic matter in zones assigned to higher SOC stocks is older, and *vice versa*.

The topsoil organic matter (30 cm) declined in age from the polar to the warm temperate regions and started to increase again for the subtropical and tropical regions (Fig. 2). This suggests a lower residence time of C and/or higher rates of fresh C inputs at warmer biotemperature levels, whereas we assume an interrupted pattern leading to a systematic change in processes affecting SOC persistence in subtropical and tropical zones. Separated into the humidity zones, the highest radiocarbon ages were found in the dry (both steppe and forest) zones, but not in the driest desert zones. The age declined strongly from dry forest to humid zones. In total, a distinct difference exists in the geographical-climate pattern found for SOC stocks and radiocarbon age in the first 30 cm of the soil. We interpret this as the respective combination of SOC persistence processes most likely differing interzonally, but not intrazonally.

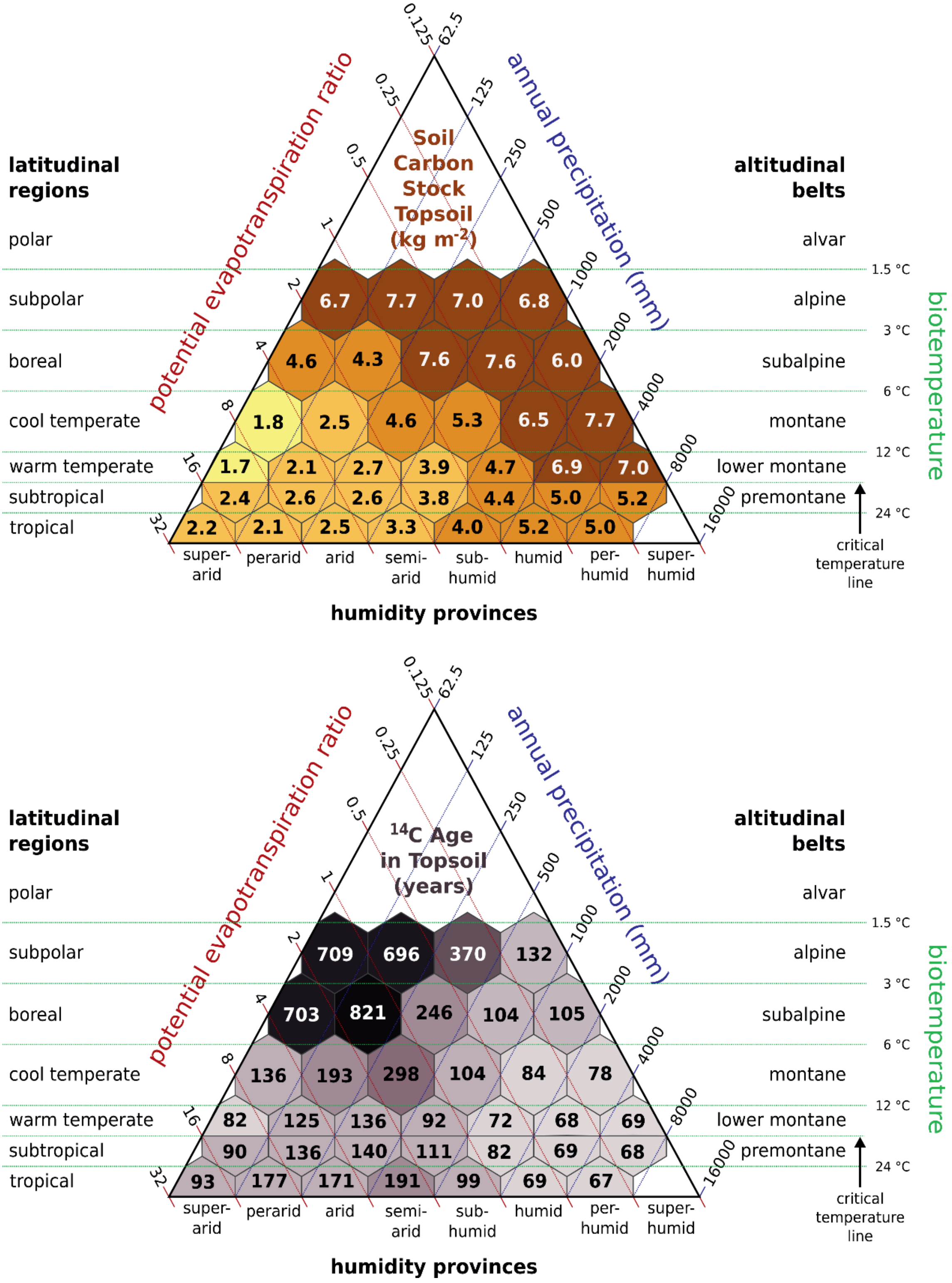

Figure 2: Mean SOC stock and carbon age (^{14}C) of the topsoil (30 cm) in the HLZ. The format of the figure is based on the HLZ classification scheme digitally created by Peter Halasz (2007): Holdridge Life Zone Classification scheme. Date: 2007-03-03 (https://commons.wikimedia.org/wiki/File:Lifezones_Pengo.svg).

5 Conclusion

We are not certain why *Post* et al. (1982) started with HLZ rather than any other classification system, such as Köppen–Geiger (LIT) and Troll / Paffen (*Peel* et al., 2007), and these warrant further testing as well. Processes of SOC persistence differ with climate, and it will be challenging to identify the underlying dominating pedogenic process controlling SOC

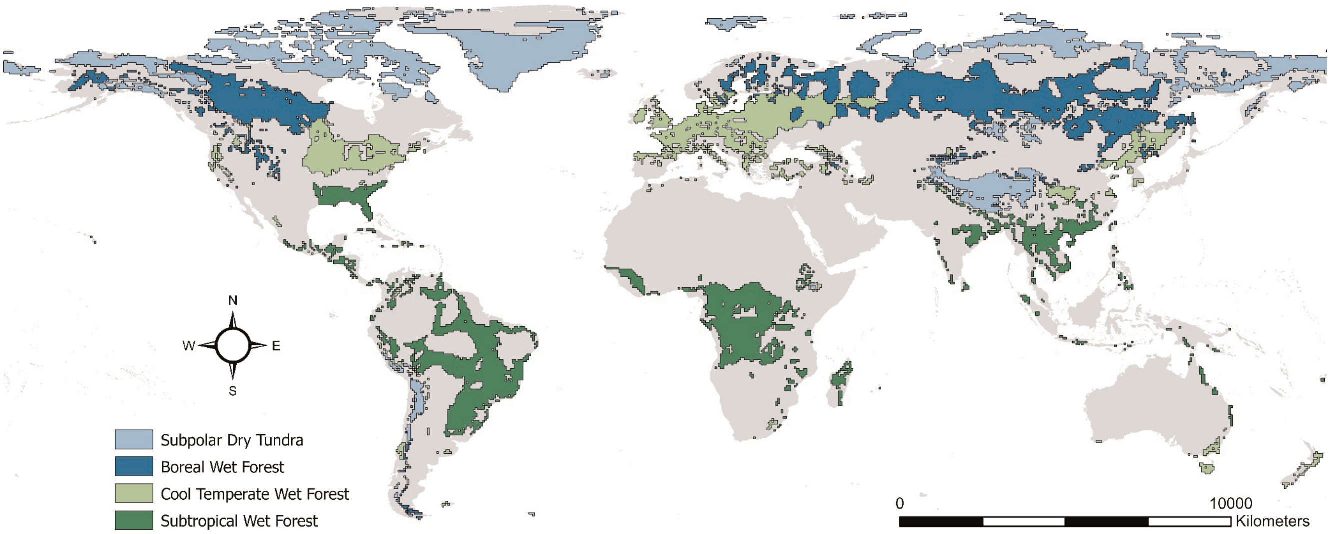

Figure 3: The distribution of the four HLZ with highest SOC stocks holding 510 Pg of the 1345 Pg of carbon globally stored in the upper meter of soil.

stocks at smaller scales. Therefore, we agree with *Hall* et al. (2020) that climate classification holds the potential to reunite diverging explanations for SOC persistence to complementarity.

SOC stocks relate to the magnitude of how soils feedback to the climate system. Since some HLZ cover only small areas despite large SOC stocks (*e.g*., # 3, 11, 17, 25, 26; Tab. 1), they may account less for the global rise in atmospheric CO_2 concentrations in situations that accelerate the release of stored SOC. Regarding C quantities, the HLZ with large areas and large SOC stocks should be the focus to advance climate protection. By upscaling, *i.e*., multiplying SOC stock with the area covered, we calculated the global amount of carbon stored in the first meter of soil for each HLZ. The most important HLZ for global SOC resources are: #9 (boreal moist forest = 169 Pg C) > #29 (subtropical moist forest = 145 Pg) > #2 (polar desert = 99 Pg) > #15 (cool temperate moist forest = 97 Pg) (Fig. 3). Together they hold 510 Pg of the 1345 Pg of carbon in the first meter of soil, which is 37.9% of the global SOC reservoir. However, the available profile data points for the polar desert are less frequent and less spatially homogenous, covering only 0.7% of the profiles integrated with the SOC database (Tab. 1). Despite these uncertainties, it seems advantageous to proceed with process-oriented studies in these four zones, as they cover a variety of climatic factors. Such focused studies could help to identify the processes that tend to dominate under specific climate conditions. Additionally, studies in the warm temperate region could reveal why soil radiocarbon ages are lowest here. Maybe the great advantage of the HLZ is that it focuses strictly on the annual data of temperature, precipitation and PET, rather than on vegetation growth requirements. HLZ compliments the bottom-up and top-down approaches, and may yet prove to be the best descriptive tool for carbon persistence studies on a global scale.

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Data Availability Statement

Data sharing not applicable to this article as used datasets are already public to be be retreaved from the named sources. So no new data were generated during the current study. We will be happy to assist if questions emerge.

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