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The lower labile carbon of surface soils in Chinese semiarid areas

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ABSTRACT
Hot water extractable organic carbon (HWOC), the labile carbon component, is often used to indicate soil organic carbon (SOC) dynamics. Nevertheless, few studies have been carried out in arid climate areas which affects our full understanding of HWOC. Here, we investigated the change in HWOC in the topsoil of different ecosystems in the southern part of the Loess Plateau in the semiarid region of China and compared it with that in other regions. The HWOC concentrations of the study area (0-10 cm) were 0.27 ± 0.12 g C kg^{-1} and 0.19 ± 0.04 g C kg^{-1} in the natural and agricultural systems respectively, and the HWOC proportions were $1.38 \pm 0.38\%$ and $2.18 \pm 0.22\%$. The HWOC concentration and proportion in the study area were much lower than the reported data in other areas, which may be affected by drought conditions. Irrigation could weaken the difference in HWOC between agricultural systems in different regions. Since HWOC is easily lost due to the impact of the arid climate, the soil carbon balance and carbon sequestration in arid and semiarid areas are relatively unstable, indicating that soil management should be improved in combination with water management.

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Agricultural system; arid area; characterisation of SOC dynamics; hot water extractable organic carbon; Loess Plateau; natural system; soil management

Introduction

As an important component of soil carbon, labile carbon stocks are more sensitive than SOC stocks (Bongiorno et al. 2019), which could greatly affect the balance of the carbon stock and flow and long-term SOC sequestration (Wiesmeier et al. 2015). Further understanding of the complex interplay between labile carbon and the environment and soil system is key to soil management (Lehmann et al. 2020; Witzgall et al. 2021). HWOC is mainly composed of carbohydrates, phenols and lignin monomers (Landgraf et al. 2006), mainly originating from soil biomass and root exudates and lysates, which are present in the soil solution, loosely adsorbed on mineral surfaces and involved in the short-term binding of aggregates (Haynes and Francis 1993; Leinweber et al. 1995). HWOC is often used as an indicator of soil because it is appropriate to characterise labile C.

The reported research shows that HWOC varies greatly in different regions, and even similar ecosystems can vary several times (Wang and Wang 2007; Spohn and Giani 2011; Jiang et al. 2017; Bongiorno et al. 2019; Yao et al. 2019; Nguyen-Sy et al. 2020; Bahadori et al. 2021; Rodriguez et al. 2021). It was found that the composition of hot water extractable carbon varies seasonally (Cepáková et al. 2016), and its content is also affected by climate (Zhou et al. 2013; Zhu et al. 2021). The great differences across regions cannot entirely be attributed to the differences in ecosystem types. How different is HWOC content in different ecosystems. Whether the proportion of HWOC in soils is similar in different ecosystem types and whether it is affected by climatic conditions. These problems are still not clearly understood. The current research is mostly carried out in humid areas, and there is still a lack of systematic research on arid areas, which limits our comprehensive understanding of HWOC.

This paper selects the Loess Plateau in the typical arid region of China for research. The objectives of this study are to (1) quantify the level of HWOC concentration in Chinese arid zone soils, (2) roughly estimate the range of relative content of HWOC, and (3) evaluate whether differences in soil HWOC are ecosystem or climate related. We estimate that HWOC can reflect ecosystem differences, with climate being an important influence, thus leading to interregional differences in soil HWOC between ecosystem types. To address these objectives,

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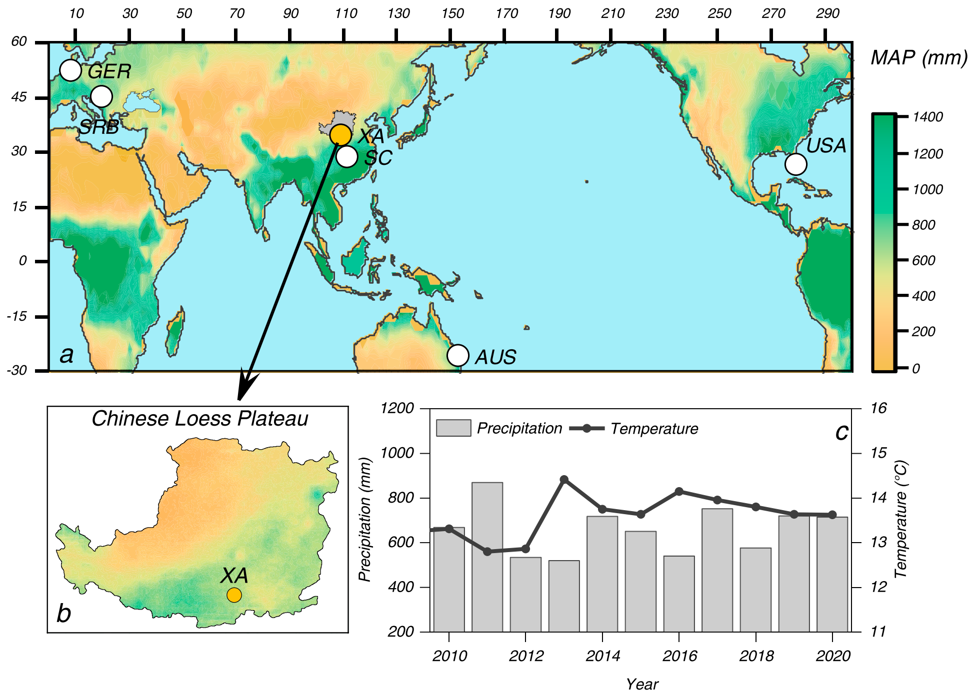

Figure 1. The location of the study area and the research sites from reported literature. (a) the sites location, XA: Xi'an, Chinese Loess Plateau, this study; AUS: Australia (Yao et al. 2019); GER: Germany (Spohn and Giani 2011); SC: South China, Hunan (Wang et al. 2007) and Guangxi (Wang and Wang 2007); SRB: Republic of Serbia (Šeremešić et al. 2013); USA: United States (Rodriguez et al. 2021). The map of mean annual precipitation (MAP) is from the data in https://psl.noaa.gov/. (b), the location of study site and Chinese Loess Plateau. (c), the mean annual temperature and annual precipitation of Xi'an, data are cited from http://data.cma.cn.

we investigated the HWOC of woodland, grassland and arable land on the Loess Plateau of China and compared the research results across regions. We validated the differences in HWOC between ecosystems and the effects of the climatic environment on the change in HWOC. This study provides HWOC data for soils in Chinse arid regions and provides suggestions for improving soil organic C management.

Materials and methods

Site selection

The study area is in Xi'an (34°N, 108°E), the southern region of the Loess Plateau, China (Figure 1). The study area belongs to a semiarid area with a mean annual temperature of 14.3°C and a mean annual precipitation of 553.5 mm (1988-2017, http://data.cma.cn). The natural vegetation in the study area is forest grassland. This area is also an agricultural area with a long history, where mainly wheat, corn, etc., are planted. This region was selected for a comparative study of a natural system and agricultural system under semiarid climate conditions and an analysis of HWOC change through comparison with published data from other regions. The selection criteria of sample sites included the following factors: a) the original land use mode or vegetation growth state must have been maintained for at least 10 years, b) the sample sites must have no grazing activities or excessive human interference, and c) the surrounding areas of the sample sites must be flat without obvious topographic changes. Based on these criteria, a cropping site that had been cultivated for 30–40 years, where mainly winter wheat, corn and vegetation, etc., have been planted, was selected as the agroecosystem. We chose a 40 m × 15 m sample plot where corn had grown within the past 5 years. The compared areas of 5 woodlands and 3 grasslands, which had been protected by the Department of Conservation for 10 years, were selected as the natural ecosystem. The woodland mainly grows pine, poplar, and gingko. The grassland mainly grows *Zoysia japonica*, *Ophiopogon japonicas*, and bermudagrass.

Soil sampling

Fifty and thirty-three soil cores, 10 cm deep with a 3-cm diameter, were collected from woodland and grassland, respectively between September 2018 and August 2019. The sampling time was monthly. Three samples were collected from a random selection of sites over each sample plot. Soil cores from each site were split into depth increments of 0–5 and 5-10 cm. The three

Table 1. The primary extraction conditions of hot water extractable organic carbon (HWOC).

Site	Location	Soil/water ratio	Temperature	Duration	Author(s)
AUS	Australia	1:5	70 °C	18 h	Yao et al. (2019)
GER	Germany	5g:25ml	—	60 min	Spohn and Giani (2011)
GX	Guangxi, China	4g:20ml	70 °C	18 h	Wang and Wang (2007)
HN	Hunan, China	20g:100ml	100 °C	1 h	Wang et al. (2007)
HN	Hunan, China	1:10	80 °C	16 h	Zhang et al. (2009)
SRB	Republic of Serbia	10g:40ml	80 °C	16 h	ŠermeŠiĆ et al. (2013)
USA	United States	3g:30ml	80 °C	16 h	Rodriguez et al. (2021)
XA	Xi'an, China	50g:200ml	85 °C	150 min	This study

samples from each site were combined and homogenised to generate one composite sample per depth per site. Soil samples were sealed with sterile sample bags (Nasco Whirl-Pak), kept on ice in the field and stored at −20°C in the lab until processing. Seventeen soil cores were collected from the cropping sample plot with the same method between April and August 2015. The sampling time was weekly.

Sample analysis

Small stones and plant residues, etc., were removed manually after the samples were air dried. The samples were ground with an agate mortar and sieved through a 2 mm sieve. The samples were acidified to remove inorganic carbon. One part of each sample was dried at 105°C for 3 h for SOC analysis, and one part was prepared for HWOC extraction. HWOC extraction was determined according to the modified method of Ghani et al. (2003). We optimised the extraction conditions considering the low background content of SOC in the study area and the large sample mass for extraction. Two hundred millilitres of deionised water was added to 50 g of each sample, which was then shaken and extracted in an 85°C water bath for 150 min. The supernatant was filtered through a 0.45 μm cellulose nitrate membrane (Whatman™) filter after centrifugation at 4000 rpm. The extract was freeze-dried for 48 h to remove water.

The prepared samples were determined by elementary C analysis with combustion at 980°C by a Vario EL III analyzer (Elementar, Germany). Approximately 20 mg of each prepared sample was weighed in tin vessels and automatically loaded into the combustion oven at 980°C. The formed CO_2 gases were determined by a thermal conductivity detector (TCD). The standard deviations of the working standard and duplicate samples were less than 0.4%. Sample analysis was carried out at the Institute of Earth Environment, Chinese Academy of Sciences.

Data analysis

The carbon content of the extract was converted into the HWOC concentration of the soil according to the sample mass. One-way analysis of variance was used to analyze the difference in soil carbon between the 0–5 and 5-10 cm depths of woodland, grassland and cropland. The relationships between the SOC and HWOC fractions were examined using linear regression. The statistical analysis of data was performed using R software.

The HWOC proportion in SOC represents the relative concentration of HWOC.

Referenced HWOC data were chosen from the published literature with clear descriptions of the research site, vegetation, experimental design, sample depth and extraction method (Table 1). We grouped the HWOC data into woodland, grassland and arable land for comparison with this study. When there are multiple data results in the literature, the average value is taken to represent this site.

Results

The SOC and HWOC concentrations (0-10 cm) in the natural system (21.96 ± 3.75 g kg^{-1} and 0.27 ± 0.12 g C kg^{-1}, respectively) were higher than those in the agricultural system (8.65 ± 2.06 g kg^{-1} and 0.19 ± 0.04 g C kg^{-1}, respectively). The SOC content in grassland was higher than that in woodland and arable land, and the difference among the systems was significant ($P < 0.05$). However, the HWOC content decreased gradually from woodland and grassland to arable land (Figure 2). The difference between the natural system and agroecosystem was significant ($P < 0.01$), but the difference between woodland and grassland was not significant.

Comparisons between the depth intervals showed that in natural and agroecosystems, both SOC and HWOC contents were higher at 0-5 cm (23.39 ± 3.87 g kg^{-1} and 0.33 ± 0.12 g kg^{-1} in natural, and 8.96 ± 2.09 g kg^{-1} and 0.2 ± 0.04 g kg^{-1} in agroecosystem) than at 5-10 cm (20.44 ± 2.94 g kg^{-1} and 0.21 ± 0.07 g kg^{-1} in natural, and 8.33 ± 2.06 g kg^{-1} and 0.18 ± 0.04 g kg^{-1} in agroecosystem). There was a significant difference between the two depths in the natural system ($P < 0.05$), but in the agroecosystem, there was no significant difference (Figure 2). At the 5-10 cm

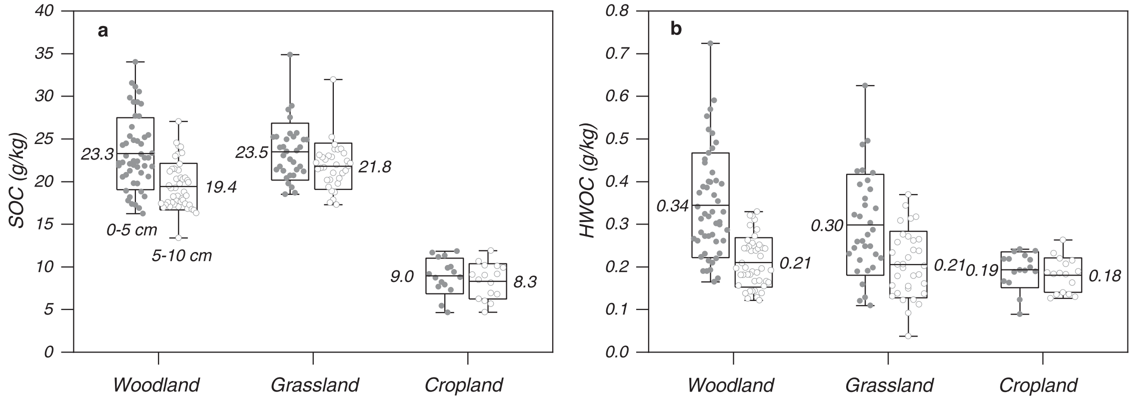

Figure 2. The carbon content of the topsoil of the study area. (a) soil organic carbon (SOC) content at 0-5 cm and 5-10 cm, (b) hot water extractable organic carbon (HWOC) content at 0-5 cm and 5-10 cm. The box shows the mean value and ±1σ standard deviation range, and the whisker shows the outlier data.

depth, the difference in the HWC content between the natural and agroecosystems was not significant but was significant at 0-5 cm ($P < 0.01$).

The results of the HWOC proportion show that the relative concentrations of HWOC in the study area were 1.28 ± 0.36%, 1.09 ± 0.39% and 2.19 ± 0.22% in woodland, grassland and arable land, respectively (Figure 4c). In contrast, the HWOC proportion in other areas ranged from 1-9% (Figure 4d-g). The HWOC proportion of the study was basically in the lower limit of the variation range.

Discussion

Low HWOC content of topsoil in a natural system under drought conditions on the Loess Plateau

The content of HWOC in the topsoil of the Loess Plateau natural system was significantly lower than that in other regions (Figure 3d, e), which may first be due to the low background concentration of carbon in the area. Due to the arid climate, the biomass and SOC of the Loess Plateau are generally low (Soil Subcenter, National Earth System Science Data Centre, National Science & Technology Infrastructure of China (http://soil.geodata.cn)). As the water-extracted component of SOC, HWOC showed a significant correlation with SOC (Spohn and Giani 2011; Yao et al. 2019; Figure 4b), which also existed in the study area (Figure 4a). The low SOC in the Loess Plateau will inevitably lead to a low HWOC.

At the 0-10 cm depth, the HWOC of grassland in the study area (annual average temperature of approximately 14°C, annual precipitation of approximately 550 mm) was 80% lower than that of Australia (annual average temperature 21.4°C, annual precipitation 1038 mm). Annual temperature, aridity and precipitation can express effects on soil C function through litter incorporation and stability (Eldridge et al. 2020). Moreover, under the influence of root-derived C (Kuzyakov and Domanski 2000; Jones et al. 2009), the HWOC content in different ecosystems under drought conditions would be expected to be lower than that in relatively humid areas, which may further lead to regional differences in HWOC. Unfavourable water conditions on Loess Plateau are not conducive to SOC accumulation and labile C formation.

Based on the method of the climate-diagram maps of Walter et al. (1975), we distinguished the dry and wet conditions by the ratio of annual precipitation to annual average temperature, that is, the corresponding precipitation per degree centigrade. The results showed that the HWOC content tended to increase with hydrothermal conditions (Figure 3). The woodland HWOC of this study was approximately 70% lower than that of Australia and South China (Zhang et al. 2009; Yao et al. 2019). The results in Europe were ten times higher than those in this study (Spohn and Giani 2011).

It should also be noted that there are differences in the extraction conditions of HWOC (Table 1). Assume the aim that different researchers optimise the extraction conditions was to obtain the maximum extraction amount. The referenced HWOC data can be considered to represent the status of the ecosystem or region at that time.

Effects of irrigation on the HWOC of agroecosystem topsoil on the Loess Plateau

The SOC and HWOC contents of arable land in the study area were also lower than those in other regions (Figure 3c, f). For example, the HWOC was 50% lower than that in Australia; however, this difference was obviously smaller, except for the USA, than that in the natural system (Figure 3). This result may relate to the impact of land management on the agricultural system. The Loess Plateau is highly vulnerable to drought. Farmland on the Loess Plateau depends on irrigation, which is also the most common and important human impact mode in the global agricultural system. Physico-chemical protection of SOC from decomposers is limited in arid soils (Doetterl et al. 2015). Irrigation weakens the impact of climatic conditions on the agricultural system (Delgado-Baquerizo et al. 2017) and partially offsets the low HWOC content caused by drought. The influence of lower precipitation on the agricultural system HWC in arid areas and the difference from humid areas also weakened. High precipitation in southern Florida is favourable for carbon accumulation and high HWOC values in everglades agricultural areas (Rodriguez et al. 2021, Figure 3f). At the 0-5 cm and 5-10 cm depths in the study area, the stable soil moisture and HWOC content of cultivated soil and the significantly reduced soil moisture and HWOC content of woodland and grassland supported this.

Irrigation, fertiliser application and tillage affect SOC and HWOC (Ghani et al. 2003; Šeremešić et al. 2013; Bongiorno et al. 2019). Since there is no description about agricultural tillage in all five studies from arable land, tillage was considered to have no effect. AUS, GER and the USA were considered to have no fertilisation because it's not clear in the literature. For the studies with fertiliser application (SRB and HN), we chose the results from the blank control to get close to the natural state for comparison. Fertiliser application may lead to a certain uncertainty in the comparison of arable land HWOC across regions, and the comparison of different ecosystem types in the same region may not be greatly affected.

Ecosystem differences in the HWOC content on the Loess Plateau

The order of the changes in HWOC content showed that in the Loess Plateau, woodland was higher than grassland and arable land (Figure 3). The difference in HWOC content between natural and agricultural systems is mainly due to the different C input/output equilibrium processes. On the one hand, the allocated C beneath the ground is higher for natural systems than for agricultural ecosystems (Kuzyakov and Domanski 2000; Pausch and Kuzykov 2018), and the underground input of root C contributes more to SOC accumulation than to the aboveground input of leaves and residues (Schmidt et al. 2011; Delgado-Baquerizo et al. 2017). On the other hand, organic matter input will increase labile C fractions (Bongiorno et al. 2019). The crop straw in the study area was removed for feed processing. The crop harvest also greatly reduces the C input of the arable land soil, which destroys the C balance and expands the difference with the natural system. The SOC content was significantly lower than that in the natural system ($P < 0.01$), and the HWOC content was also significantly lower than that in the natural system ($P < 0.01$) (Figure 3).

The relationship between HWOC and soil moisture in the study area shows that the difference in soil moisture also influences the HWOC. No direct correlation was observed between soil moisture and HWOC in woodland and arable land in this study. The weak correlation in grassland showed that there was a certain connection between them. We suggest that this may be related to farmland irrigation and the redistribution of water by the deep roots of woodland trees. There is evidence that the extracted organic carbon from topsoil varies greatly under different water conditions (Singh et al. 2021). The higher wetland HWOC than upland in Australia (Yao et al. 2019) and the high HWOC in peat soil (Rodriguez et al. 2021) show the influence of water change. On the Loess Plateau, the soil moisture of the arable land ($23.02 \pm 4.21\%$) was significantly higher than that of the natural systems ($13.84 \pm 3.08\%$) ($P < 0.01$). The relatively dry topsoil of the natural system may limit the ability of HWOC to migrate with water. The shallow root distribution makes herbaceous plants vulnerable to soil moisture, which has little correlation with SOC but a weak correlation with HWOC. Upward hydraulic redistribution of deep roots of the trees (Brooks et al. 2002) and agricultural irrigation weakens the correlation with water in woodland and arable land, also leading to more accumulation of HWOC in the surface soil (Figure 2b). This also explains why the depth difference in HWOC in this study was more significant in the natural system. The soil moisture was significantly different between the two depths in the natural system. However, in the agricultural system, there was no significant difference in soil moisture and HWOC content between the two depths.

Activity of topsoil of the Loess Plateau indicated by HWC proportion

The HWOC proportion in SOC could be used to compare activity between regions and ecosystems because it could avoid the order of magnitude difference in labile content (Bongiorno et al. 2019; Bahadori et al. 2021). In other regions, the HWOC proportion of the agricultural system was not higher than that of the natural system (Figure 4d-g). This may be because woodlands and

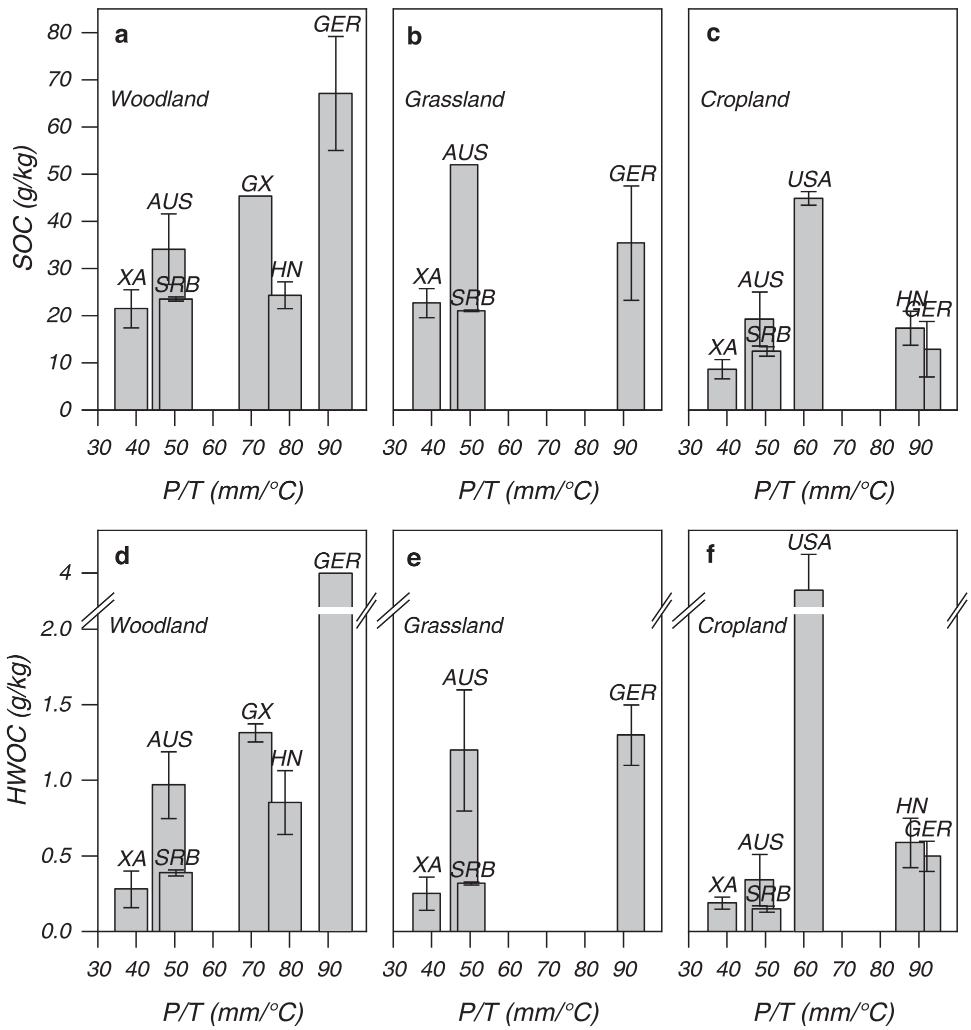

Figure 3. Comparison of soil organic carbon (SOC) and hot water extractable organic carbon (HWOC) contents between the study area and literature reports. (a) SOC content of woodland, (b) SOC content of grassland, (c) SOC content of arable land, (d) HWOC content of woodland, (e) HWOC content of grassland, and (f) HWOC content of arable land. P/T is the ratio of annual precipitation to annual average temperature, which represents the corresponding precipitation per degree centigrade. AUS: Australia; GER: Germany; SC: South China, Hunan and Guangxi; SRB: Republic of Serbia; USA: United States; XA: Xi'an, Chinese Loess Plateau. Error bars show 1σ standard deviation. XA, AUS, HN and USA were 0-10 cm, and GX, SRB and GER were 0-20 cm.

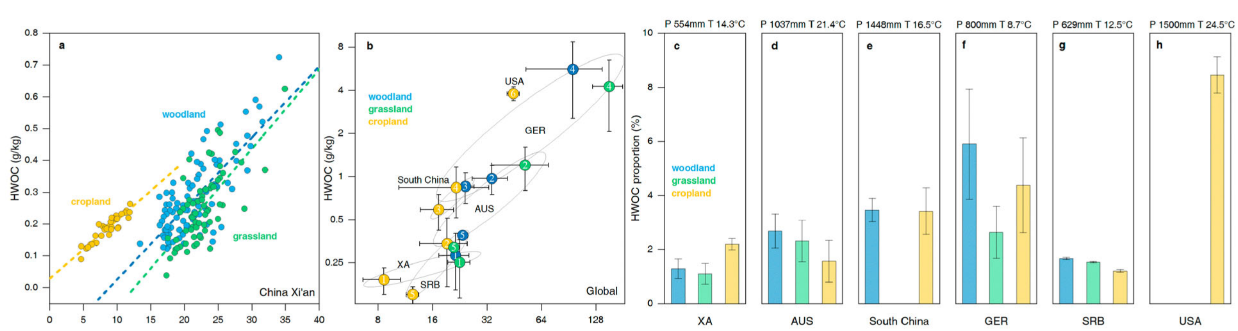

Figure 4. Hot water extractable organic carbon (HWOC) content and HWOC proportion. (a) HWOC and soil organic carbon (SOC) contents of the study area in 0-10 cm, (b) HWOC and SOC contents from the literature reports, (c) HWOC proportion of the study area, (d), (e), (f), (g) and (h) HWOC proportion from the literature reports. AUS: Australia; GER: Germany; SC: South China, Hunan and Guangxi; SRB: Republic of Serbia; USA: United States; XA: Xi'an, Chinese Loess Plateau. Error bars show 1σ standard deviation.

grasslands usually contain more nonhumic particulate organic matter that can be easily extracted by water (Bahadori et al. 2021). In topsoil, it was 1-6% in agricultural systems in Europe (Bongiorno et al. 2019) and about 2.5% and 1.3% in natural and agricultural systems in Australia, respectively (Bahadori et al. 2021).

However, on the Loess Plateau, the HWOC of the agricultural system was higher than that of the natural system (2.19 ± 0.22% and 1.20 ± 0.38%, respectively). We suggest that this may be because of the alleviation of soil drought through irrigation and the disturbance reduction by no-tillage which resulted in a corresponding increase in labile C (Bongiorno et al. 2019). It was found that in the everglades agricultural area, the HWOC proportion of peat soil was significantly high (Rodriguez et al. 2021), and natural peatland soil and even compost contained much more HWOC (Heller and Weiß 2015; Kalisz et al. 2015).

The HWOC proportion of woodland was significantly higher than that of grassland (1.28 ± 0.36% and 1.09 ± 0.39%, respectively, $P < 0.01$) (Figure 4c). This result, consistent with other areas, can be attributed to the high productivity characteristics of woodland vegetation supported by rapid nutrient cycling in topsoil.

On the arid Loess Plateau, the concentration and proportion of HWOC is generally low compared with other regions. Nevertheless, in the agricultural system, the difference in the HWOC proportion weakened and was significantly higher than that in the natural system. This is different from the relatively high HWOC proportion of natural systems in other regions. This may be due to the alleviation of soil drought through irrigation. On the arid Loess Plateau, drought and land use change led to great SOC loss (Zhang et al. 2015) and limited the physico-chemical protection of SOC (Doetterl et al. 2015); as a result, the erosion risk of the area could have a great impact on the soil labile component. Soil management improvement should focus on strengthening water use efficiency. For the wide arid area in northern China, improving soil properties and preventing degradation are very important for the long-term carbon storage of regional soil. Due to the limited research data and the differences in HWOC extraction methods, there is still a certain uncertainty in the comparative analysis of this study. Obtaining more detailed data classification to reduce uncertainty is important for a comprehensive and accurate understanding of HWOC and is worth further research.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Research Data

Data of soil SOC and HWC in southern Chinese Loess Plateau associated with this article can be accessed at https://data.mendeley.com/datasets/t9vzjvdvn3.

Notes on contributor

All authors participated in data collation. Z.F. developed aims, research questions extracted data and undertook most of the analyses, supported by W.Z. Z.F. drafted the manuscript, all authors contributed to revisions and gave final approval for publication.

References

Bahadori M, Chen C, Lewis S, Boyd S, Rashti MR, Esfandbod M, Garzon-Garcia A, Zwieten LV, Kuzyakov Y. 2021. Soil organic matter formation is controlled by the chemistry and bioavailability of organic carbon inputs across different land uses. Sci Total Environ. 770:145307.

Bongiorno G, Bünemann EK, Oguejiofor CU, Meier J, Gort G, Comans R, Mäder P, Brussaard L, Goede R. 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecol Indic. 99:38–50.

Brooks JR, Meinzer FC, Coulombe R, Gregg J. 2002. Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. Tree Physiol. 22:1107–1117.

Cepáková Š, Tošner Z, Frouz J. 2016. The effect of tree species on seasonal fluctuations in water-soluble and hot water-extractable organic matter at post-mining sites. Geoderma. 275:19–27. doi:10.1016/j.geoderma.2016.04.006.

Delgado-Baquerizo M, Eldridge DJ, Maestre FT, Karunaratne SB, Trivedi P, Reich PB, Singh BK. 2017. Climate legacies drive global soil carbon stocks in terrestrial ecosystems. Sci Adv. 3:e1602008.

Doetterl S, Stevens A, Six J, Merckx R, Oost KV, Pinto MC, Casanova-Katny A, Muñoz C, Boudin M, Venegas EZ, Boeckx P. 2015. Soil carbon storage controlled by interactions between geochemistry and climate. Nat Geosci. 8:780–783.

Eldridge DJ, Delgado-Baquerizo M, Quero JL, Ochoa V, Gozalo B, García-Palacios P, Escolar C, García-Gómez M, Prina A,

Bowker MA, et al. 2020. Surface indicators are correlated with soil multifunctionality in global drylands. J Appl Ecol. 57:424–435.
Ghani A, Dexter M, Perrott KW. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. Soil Biol Biochem. 35:1231–1243.
Haynes PJ, Francis GS. 1993. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. Journal of Soil Science. 44:665–675.
Heller C, Weiß K. 2015. Approaching a standardized method for the hot-water-extraction of peat material to determine labile SOM in organic soils. Commun Soil Sci Plant Anal. doi:10.1080/00103624.2015.1019082.
Jiang Q, Xu Z, Hao Y, Dong H. 2017. Dynamics of soil labile carbon and nitrogen pools in riparian zone of Wyaralong Dam in Southeast Queensland, Australia. J Soils Sediments. 17:1030–1044.
Jones DL, Nguyen C, Finlay RD. 2009. Carbon flow in the rhizosphere: carbon trading at the soil-root interface. Plant Soil. 321:5–33.
Kalisz B, Lachacz A, Glazewski R. 2015. Effects of peat drainage on labile organic carbon and water repellency in NE Poland. Turk J Agric For. 39:20–27. doi:10.3906/tar-1402-66.
Kuzyakov Y, Domanski G. 2000. Carbon input by plants into the soil. Review. J Plant Nutr Soil Sci. 163:421–431.
Landgraf D, Leinweber P, Makeschin F. 2006. Cold and hot water-extractable organic matter as indicators of litter decomposition in forest soils. J Plant Nutr Soil Sci. 169:76–82. doi:10.1002/jpln.200521711.
Lehmann J, Hansel CM, Kaiser C, Kleber M, Maher K, Manzoni S, Nunan N, Reichstein M, Schimel JP, Torn MS, et al. 2020. Persistence of soil organic carbon caused by functional complexity. Nat Geosci. 13:529–534.
Leinweber P, Schulten HR, Körschens M. 1995. Hot water extracted organic matter: chemical composition and temporal variations in a long-term field experiment. Biol Fertil Soils. 20:17–23.
Nguyen-Sy T, Cheng W, Kimani SM, Shiono H, Sugawara R, Tawaraya K, Watanabe T, Kumagai K. 2020. Stable carbon isotope ratios of water-extractable organic carbon affected by application of rice straw and rice straw compost during a long-term rice experiment in Yamagata, Japan. Soil Sci Plant Nutr. doi:10.1080/00380768.2019.1708209.
Pausch J, Kuzykov Y. 2018. Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. Glb Chg Bio. 24:1–12.
Rodriguez AF, Gerber S, Inglett PW, Tran NT, Long JR, Daroub AH. 2021. Soil carbon characterization in a subtropical drained peatland. Geoderma. 382:114758. doi:10.1016/j.geoderma.2020.114758.
Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, et al. 2011. Persistence of soil organic matter as an ecosystem property. Nature. 478:49–56.
Šeremešić S, Milošev D, Sekulić P, Nešić L, Ćirić V. 2013. Total and hot-water extractable carbon relationship in chernozem soil under different cropping systems and land use. J Cent Eur Agric. 14(4):1479–1487. doi:10.5513/JCEA01/14.4.1382.
Singh S, Mayes MA, Shekoofa A, Kivlin SN, Bansal S, Jagadamma S. 2021. Soil organic carbon cycling in response to simulated soil moisture variation under field conditions. Sci Rep. 11:10841.
Spohn M, Giani L. 2011. Total, hot water extractable, and oxidation-resistant carbon in sandy hydromorphic soils-analysis of a 220-year chronosequence. Plant Soil. 338:183–192.
Walter H, Harnickell E, Mueller-Dombois D. 1975. Climate-diagram maps. Ind. Countries and the ecological climatic regions of the Earth supplement to the vegetation monographs. 8(11):1–4.
Wang QK, Wang SL. 2007. Soil organic matter under different forest types in Southern China. Geoderma. 142:349–356.
Wang K, Wang K, Peng N, Lv H, Xie X. 2007. Water extractable carbon in red soil of paddy field. Chin J Soil Sci. 38(3):447–451. in Chinese.
Wiesmeier M, Munro S, Barthold F, Steffens M, Shad P, Kögel-Knabner I. 2015. Carbon storage capacity of semi-arid grassland soils and sequestration potentials in northern China. Glb Chg Bio. 21:3836–3845.
Witzgall K, Vidal A, Schubert DI, Höschen C, Schweizer SA, Buegger F, Pouteau V, Chenu C, Mueller CW. 2021. Particulate organic matter as a functional soil component for persistent soil organic carbon. Nat Commun. 12:4115.
Yao L, Rashti MR, Brough DM, Burford MA, Liu W, Liu G, Chen C. 2019. Stoichiometric control on riparian wetland carbon and nutrient dynamics under different land uses. Sci Total Environ. 697:134127.
Zhang F, Li C, Wang Z, Glidden S, Grogan DS, Li X, Cheng Y, Frolking S. 2015. Modeling impacts of management on farmland soil carbon dynamics along a climate gradient in Northwest China during 1981-2000. Ecol Modell. 312:1–10. doi:10.1016/j.ecolmodel.2015.05.006.
Zhang J, Wang S, Wang Q, Liu Y. 2009. Content and seasonal change in soil labile organic carbon under different forest covers. Chin J Eco-Agric. 17(1):41–47. in Chinese.
Zhou X, Chen C, Wang Y, Xu Z, Duan J, Hao Y, Smaill S. 2013. Soil extractable carbon and nitrogen, microbial biomass and microbial metabolic activity in response to warming and increased precipitation in a semiarid Inner Mongolian grassland. Geoderma. 206:24–31. doi:10.1016/j.geoderma.2013.04.020.
Zhu E, Cao Z, Jia J, Liu C, Zhang Z, Wang H, Dai G, He J, Feng X. 2021. Inactive and inefficient: warming and drought effect on microbial carbon processing in alpine grassland at depth. Glb Chg Bio. 27:2241–2253. doi:10.1111/gcb.15541.