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Soil physico-chemical properties are critical for predicting carbon storage and nutrient availability across Australia

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Abstract

Soil carbon and nutrient availability play crucial roles in ecosystem sustainability, and they are controlled by the interaction of climatic, biotic, and soil physico-chemical variables. Although soil physico-chemical properties have been recognized as vital variables for predicting soil organic carbon (SOC) and nutrients, their relative influence across broad geographical scales has yet to be evaluated when simultaneously considering many other drivers. Using boosted regression tree and structural equation modelling analyses of observations from topsoil (0–10 cm) and subsoil (20–30 cm) at 628 sites across Australia, we investigated the effects and relative influence of climate (mean annual temperature and aridity index), plant productivity, soil biodiversity (bacterial and fungal richness), and soil physical (clay and silt) and chemical (pH and iron) properties on SOC content and nutrient availability (i.e. nitrogen, phosphorus, and potassium). Among these variables, we found that soil physico-chemical properties primarily predicted the continent-scale SOC storage and nutrient availability. In contrast, climate, plant productivity, and soil biodiversity played relatively small roles. The importance of physico-chemical properties was evident across soil depths and ecosystem types (i.e. tropical, temperate, arid, and cropland). Our findings point to the need to better understand the role of soil physico-chemical properties in soil carbon and nutrient cycling and including these variables in predictions of SOC and nutrient dynamics at the ecosystem to continental scale.

1. Introduction

Soils are the main terrestrial reservoir of carbon and nutrients (Quinton *et al* 2010, Carvalhais *et al* 2014), which determine soil fertility, plant growth and ecosystem sustainability (Doran and Zeiss 2000, Lal 2004), and thus soils are crucial for human well-being (Lal 2004). Soil organic carbon (SOC) and nutrient cycling are strongly interrelated (Quinton *et al* 2010, Finzi *et al* 2011), and their dynamics fundamentally determine soil functioning and are closely related to the changing climate (Delgado-Baquerizo *et al* 2013). Thus, understanding the mechanisms that control soil carbon and nutrients is crucial to successful ecosystem management and climate change mitigation (FAO 2015, Viscarra Rossel *et al* 2019). Currently, however, large uncertainties remain when predicting SOC and nutrient dynamics (Karmakar *et al* 2016, Rasmussen *et al* 2018). These uncertainties occur because models often poorly represent the current global distributions of SOC (Carvalhais *et al* 2014) or nutrients (Jobbágy and Jackson 2001) and because they may inadequately incorporate regulating factors (Tang and Riley 2015, Jeong *et al* 2017). The latter indicates shortcomings in parameterizing the controls, or neglecting some vital drivers, such as soil physico-chemical properties (Schmidt *et al* 2011, Lehmann and Kleber 2015).

Soil physico-chemical properties are associated with strong chemical bonds or closed environments protecting SOC from decomposition (Krull *et al* 2003). Physical properties such as soil texture are usually used to indicate the size distribution of mineral particles, and are considered as crucial factors affecting the soil organic matter accumulation (Dexter 2004). For instance, silt and clay particles can protect soil organic matter against microbial mineralization by stabilizing them on mineral surface (Six *et al* 2002a). Chemical properties are usually associated with chemical bonding of SOC to mineral particles, reducing the degrading ability of enzymes and decomposers (Six *et al* 2002a). For instance, mineral availability (e.g. iron) is considered as a key regulator of soil carbon storage through bonding mechanisms (e.g. Yu *et al* 2017). Soil pH also significantly regulates SOC, because it influences organic matter turnover, soil nutrient bioavailability and other soil processes (Kemmitt *et al* 2006), as well as microbial biodiversity (Fierer and Jackson 2006). A growing body of empirical and modelling research indicates that physico-chemical properties exert considerable roles in controlling SOC (e.g. Torn *et al* 1997, Schmidt *et al* 2011, O'Brien and Jastrow 2013, Doetterl *et al* 2015, Lehmann and Kleber 2015, Abramoff *et al* 2018, Rasmussen *et al* 2018, Cotrufo *et al* 2019, Hemingway *et al* 2019). In fact, multiple drivers such as physico-chemical properties and climate are not separate, but interact with one another to regulate SOC dynamics, which was well documented in recent studies from local to continental scales (e.g. Doetterl *et al* 2015, Luo *et al* 2017, Li *et al* 2018, Hemingway *et al* 2019, Viscarra Rossel *et al* 2019). For example, based on machine-learning with 5721 topsoil measurements, Viscarra Rossel *et al* (2019) showed that climate, elevation, and soil properties were dominant controls on SOC fractions and potential vulnerability across Australia. However, their relative contribution remains elusive when considering the concurrent regulatory effects of climate, physico-chemical properties, and other recognizably important drivers (such as plant productivity and soil biodiversity).

Besides soil carbon, soil nutrient availability also plays crucial roles in sustaining soil quality and plant productivity (Quinton *et al* 2010). Soil physical drivers may affect nutrient levels through mineral specific surface area (Kome *et al* 2019); chemical properties such as pH also strongly regulate soil nutrient bioavailability (Neina 2019). However, the relative importance of physico-chemical properties in predicting nutrient availability has received less attention. Thus, the question now arises as to what degree physico-chemical properties affect SOC and nutrient (i.e. soil available nitrogen (N), potassium (K), and phosphorus (P)) availability when considering interactions of climatic, biotic, and physico-chemical properties factors across broad ecosystem types at a large scale.

Here, we hypothesize that soil physico-chemical properties primarily predict SOC and nutrients at a continental scale. To test this hypothesis, we used data of topsoil (0–10 cm) and subsoil (20–30 cm) from 628 sites across the Australian continent (figure 1). These sites include diverse ecosystem types based on climate and land use (i.e. tropical, temperate, arid, and cropland), covering wide ranges of mean annual temperature (MAT) (5.7 °C–28.0 °C), mean annual precipitation (MAP) (170–2191 mm), and altitude (1–1674 m a.s.l.), making them suitable to disentangle the relative influence-strengths of multiple drivers of SOC and nutrient availability. The wide spatial variations in SOC and nutrients are shown in figure 1, and ranges of some key soil properties among the 628 sites are shown in table S1 (available online at stacks.iop.org/ERL/15/094088/mmedia).

In the present study, we included climate (i.e. MAT and aridity index (A.I., potential evapotranspiration/MAP)), plant productivity (indicated by NDVI, the normalized difference vegetation index), soil microbial alpha diversity (i.e. bacterial and fungal richness), physical properties (i.e. silt and clay content), and chemical properties (i.e. soil pH and extractable iron (Fe)) as interacting drivers of SOC and nutrients. We conducted boosted regression tree (BRT) analyses (Elith *et al* 2008) to reveal the relative influence of physico-chemical properties in controlling SOC and nutrients while simultaneously accounting for multiple other drivers (i.e. climate, soil biodiversity, and plant productivity), and structural equation modelling (SEM) to identify indirect and direct influences of these drivers on SOC and nutrients (see our *a priori* model in figure S1).

2. Materials and methods

Data used in the present study were obtained from the Biome of Australian Soil Environments (BASE) project, a database of soil microbial diversity and associated sample specific contextual properties (Bissett *et al* 2016). Sample ID's used in the present study are included in table S2. All data were downloaded as sample specific contextual data and amplicon sequence variant (ASV) abundance matrices. Data generation methods are described briefly below.

2.1. Study sites and soil sampling

A subset sample from 628 sites across Australia (figure 1) were used in this study. These sites span an Australian continental scale, covering diverse climate conditions, above-ground productivities, and soil properties. In order to test whether the importance of physico-chemical properties on SOC and nutrients were maintained under different environmental and soil conditions, we classified ecosystems into tropical, temperate, and arid ecosystem types (Köppen classification). We also created a fourth category, cropland, due to the intense management where farming may change physico-chemical properties (e.g. through breaking up aggregates) (Six *et al* 2002b). Cropland sites were distributed across tropical, temperate, and arid climates but treating them as a single category was justified based on characteristics of SOC and available nutrients. Grassland and shrubland were dominant in tropical (~32%) and

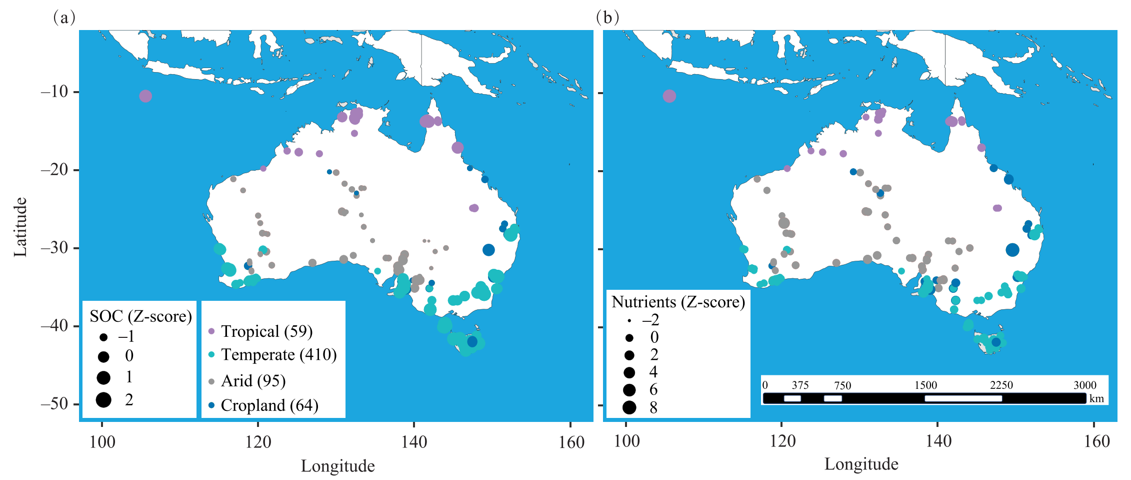

Figure 1. Spatial maps of (a) soil organic carbon (SOC, Z-score) and (b) nutrients (Z-score) in the topsoil (0–10 cm) among 628 sites across Australia. Nutrients are indicators of available nitrogen, phosphorus, and potassium. The number in brackets indicates the sample size of each ecosystem type classified by climate or cropland (because of how divergent soil characteristics were in the latter category; figure 2).

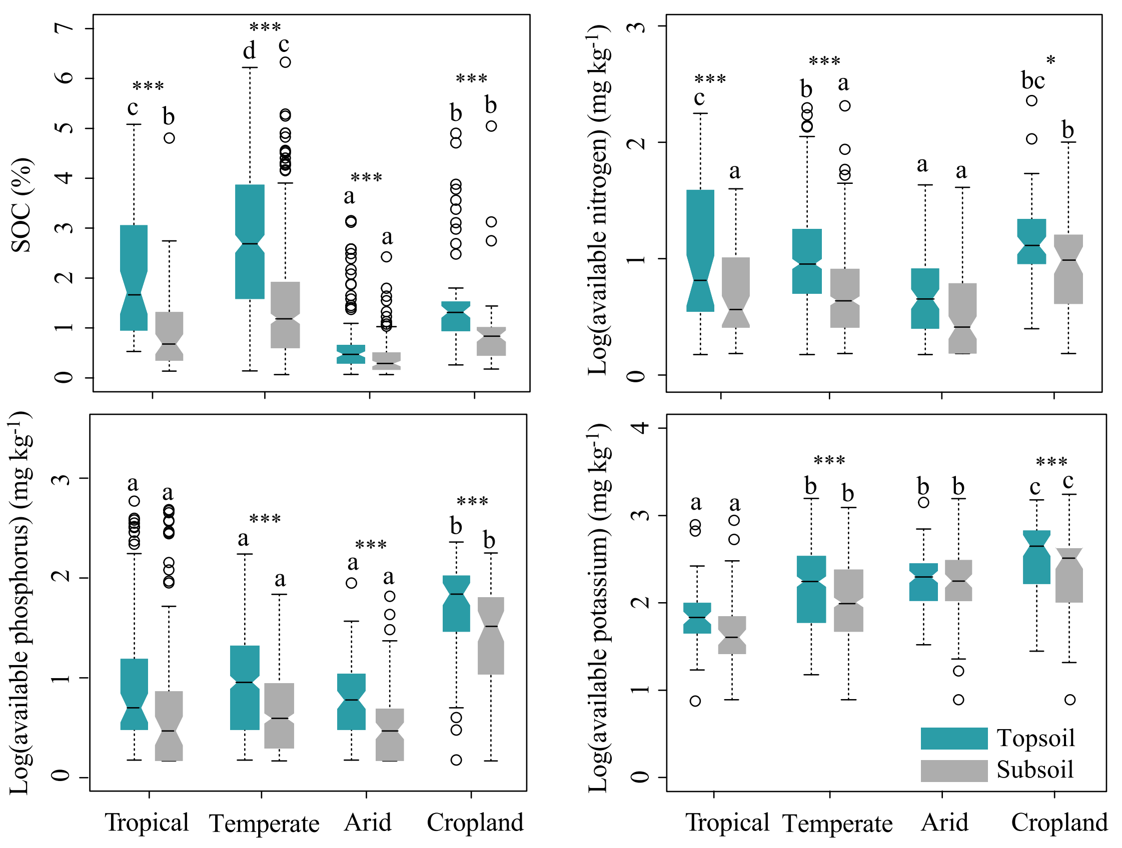

Figure 2. Box plots of soil organic carbon (SOC) and log-transformed available nutrient concentrations among different ecosystems based on climate and land use across Australia. Available nitrogen is the total of nitrate and ammonium. The lower and upper ends of the boxes are the 25th and 75th percentiles; the line across the middle of the box is the median value; and circles are outliers. The same letters at topsoil (0–10 cm) or subsoil (20–30 cm) indicate no significant difference among ecosystems using one-way ANOVA at $P = 0.05$. Asterisks indicate difference between the topsoil and subsoil using paired sample t-test with $^*P < 0.05$ and $^{***}P < 0.001$. $n = 59$, 410, 95, and 64 in tropical, temperate, arid, and cropland, respectively.

arid (~51%) sites, while temperate sites were dominated by forest and woodland (~54%).

Soil sampling followed the standardized methods (Bissett *et al* 2016). In brief, nine soil samples at two depths (0–10 and 20–30 cm) were collected from a 25 × 25 m plot at each site. The nine soil samples were then thoroughly homogenized by depth and site. Thus, 1256 soil samples (two depths × 628 sites) were included in the present study.

2.2. Climate and plant productivity

Climatic data including MAT and A.I. were obtained from the Worldclim database (Hijmans *et al* 2005) using ESRI ArcMap (Version 10.3). We used NDVI to indicate plant productivity (Pettorelli *et al* 2005, Delgado-Baquerizo *et al* 2016, Delgado-Baquerizo *et al* 2017), and this proxy of productivity index was derived from the MODIS Terra satellites. The mean value of NDVI with 0.1° resolution was calculated for the periods of 2011–2014 because all soil samples were collected during these periods.

2.3. Soil property analyses

Soil properties of each site were measured using the unified protocols described by Bissett *et al* (2016). Briefly, soil texture was measured by using a standardized particle sedimentation method (Indorante *et al* 1990). SOC concentration was measured using the Walkley-Black method (Walkley and Black 1934). Nitrate and ammonium levels were measured colorimetrically, following the extraction with potassium chloride of 1 M (Searle 1984). Available K and P were determined using the Colwell method (Rayment and Higginson 1992). Extractable Fe was extracted with diethylene triamine penta-acid (DTPA) for 2 h and then measured by atomic absorption spectroscopy (Rayment and Higginson 1992). Previous studies have shown that DTPA-extractable Fe was highly correlated to ammonium oxalate extractable Fe, representative of short-range order minerals such as ferrihydrite (Geiger and Loeppert 1986), which are associated with SOC stabilization (Rasmussen *et al* 2018). Therefore, extractable Fe might also an important factor predicting SOC. Soil pH was determined using a 1:5 soil:water ratio. Soil biodiversity levels were determined from ASV abundance matrices obtained by sequencing a portion of the Internal Transcribed Spacer region 1 (ITS1) (fungi) or the 16 S *rRNA* gene (bacteria) using Illumina MiSeq (Bissett *et al* 2016) and calculating the bias-corrected Chao index of expected richness given incomplete sampling (Chiu *et al* 2014).

2.4. Statistical analyses

Before doing all analyses, the following steps were conducted for each soil depth (i.e. topsoil and subsoil). Firstly, we normalized (log-transformed if needed) and standardized each variable using the Z-score transformation (e.g. Delgado-Baquerizo *et al* 2016, Li *et al* 2020c). Secondly, correlation analysis was conducted to evaluate the relationship between any two variables at the two soil depths for the whole database (figure S2) or within each ecosystem type (i.e. tropical, temperate, arid, and cropland) (figures S3–S6). Correlation matrices showed that soil nutrient indicators (i.e. available N, P, and K) were correlated, as were soil biodiversity indicators (i.e. Chao1 indexes of bacteria and fungi), physical properties (i.e. silt and clay), and chemical properties (i.e. extractable Fe and soil pH).

We conducted individual BRT analyses for SOC and nutrients to reveal the relative influence of a predictor variable compared with other considered variables (Elith *et al* 2008). BRT could improve model accuracy through repeatedly fitting many decision trees like Random Forest. Importantly, BRT analysis is applicable to nonlinear relationships, removes highly correlated variables, and can analyze interactive effects of different types of variables (Luo *et al* 2017). Before doing BRT analyses, we reduced the observed variables of N, P, and K to a single variable 'nutrients' using principal component analysis (PCA), to remove potential multicollinearity (Li *et al* 2020a). Finally, all observed, individual predictor variables (i.e. MAT, A.I., NDVI, bacteria, fungi, clay, silt, Fe and pH) were used in BRTs, and the relative influence of each latent predictor (i.e. climate, soil biodiversity, physical properties, and chemical properties) on SOC or nutrients was the sum of relative influences of observed predictor variables (Luo *et al* 2017, Li *et al* 2020b). For instance, the relative influence of physical properties on SOC was the sum of relative influences of clay and silt on SOC. BRTs were conducted for the Australian continent and for each ecosystem type.

We used SEM, widely applied in ecological sciences (Shipley 2001, Grace 2006), to obtain a mechanistic understanding of the spatial variation in SOC and nutrients at this continental scale. To do this, we first built an *a priori* model (figure S1), examining the indirect and direct influences of physical properties, chemical properties, climate, plant productivity, and soil biodiversity on SOC and nutrients. Climate, soil biodiversity, physical properties, chemical properties, and nutrients were latent variables reflected by observed variables (indicators). The latent variable 'nutrients' included indicators of available N, P, and K; 'climate' included indicators of MAT and A.I.; 'soil biodiversity' included indicators of Chao1 indexes of bacteria and fungi; 'physical properties' included indicators of silt and clay; 'chemical properties' included indicators of extractable Fe and soil pH. The final model was selected on the basis of overall goodness-of-fit test (Schermelleh-Engel *et al* 2003, Eldridge *et al* 2018). We repeated SEMs for each soil depth and ecosystem type. Notably, although there were some differences in factors affecting SOC and nutrients (for example plant productivity is the main source of SOC, but this is not the case for nutrients), we combined SOC and nutrients in the final SEM.

It is important to recognize that this study was mainly focused on large-scale statistical analysis. We

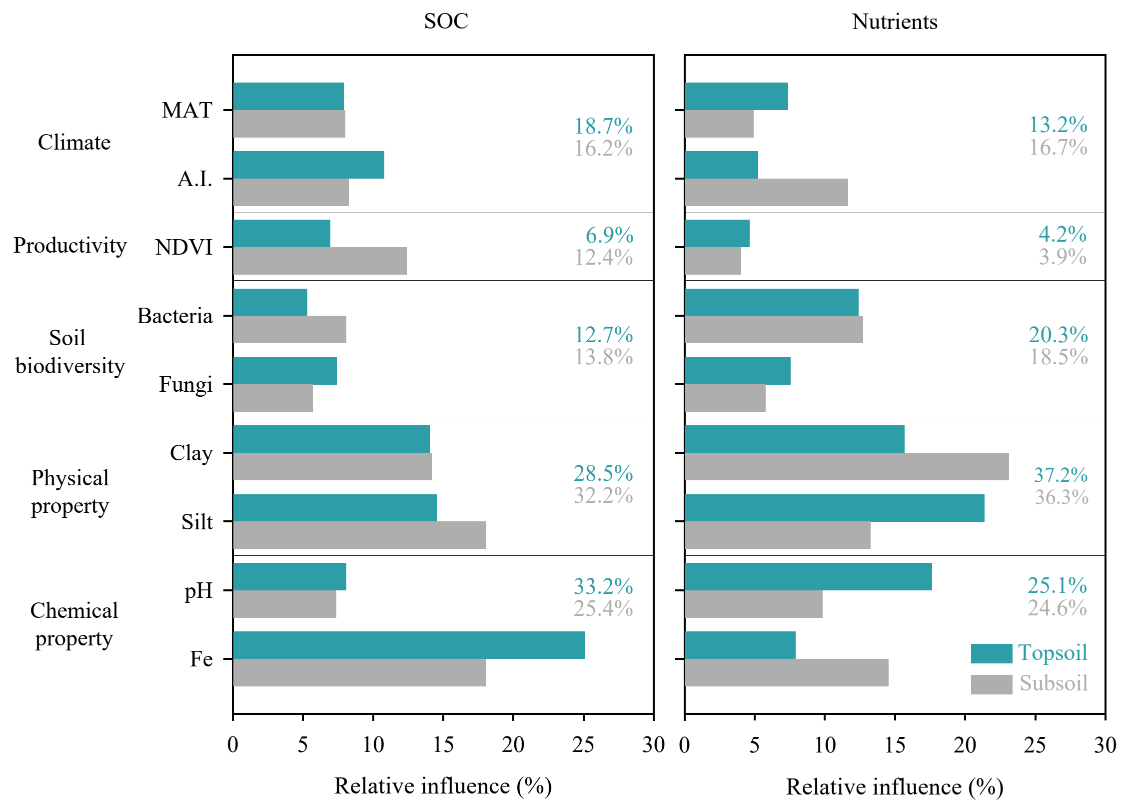

Figure 3. The relative contributions (%) of predictor variables for the boosted regression tree model of soil organic carbon (SOC, left panel) and nutrients (right panel) across Australia ($n = 628$). Green and gray numbers in each group indicate the summed relative contribution of each predictor in topsoil and subsoil, respectively. Nutrients, indicators of available nitrogen, phosphorus, and potassium; MAT, mean annual temperature; A.I., aridity index; NDVI, normalized difference vegetation index; Fe, extractable iron.

highlight that the BRT analyses show the distinct responses of SOC and nutrients to the drivers under investigation, whereas the SEM analyses demonstrate the integrated influence of those properties on the interacting SOC and nutrient contents across the study area. Thus, we used BRT to identify the relative importance of factors controlling SOC and nutrient availability when simultaneously considering all factors, and SEM to analyze their direct and indirect effects. These two approaches provided complementary insights into the factors controlling SOC and nutrients at a continental scale or within different ecosystem types. For example, results from BRTs were not affected by our prior knowledge because BRT does not depend on an *a priori* model of hypotheses. Because SEM relies on *a priori* hypotheses, it allows us to explore the direct, indirect, and interactive effects of variables affecting SOC and nutrients; importantly, our structural equation models acknowledge that SOC and nutrients are significantly correlated with each other as well. Moreover, SEM is an especially useful approach for large-scale studies (Grace 2006).

Spatial map, correlation matrices, PCA, and BRT analyses were conducted using R (R 3.4.2) and the packages 'ggbiplot2', 'PerformanceAnalytics', 'devtools', 'ggbiplot', and 'dismo'. SEM analyses were conducted with IBM SPSS Amos (Version 22.0).

3. Results

3.1. Soil carbon and nutrient levels

Ranges of some key soil properties among the 628 sites are shown in table S1. SOC and available nutrient concentrations showed wide variations across the Australian continent (figure 1). SOC and available nutrients differed significantly among ecosystem types (figure 2). For instance, topsoil SOC contents were significantly higher in temperate followed by tropical, cropland, and arid ecosystems (figure 2). Moreover, in most ecosystems, topsoil had significantly higher SOC and nutrient availability than subsoil (figure 2). These differences among ecosystems and soil depths enabled us to test whether the effects of soil physico-chemical properties on SOC and nutrients were maintained under different environmental or soil conditions.

3.2. Soil physico-chemical properties played the most important role

Results from BRTs showed that physico-chemical properties were more important than other drivers of SOC and nutrients in both soil depths (figure 3). For topsoil SOC content, chemical properties had the highest relative importance followed by physical properties, climate, soil biodiversity, and productivity; for nutrients in both depths, physical properties

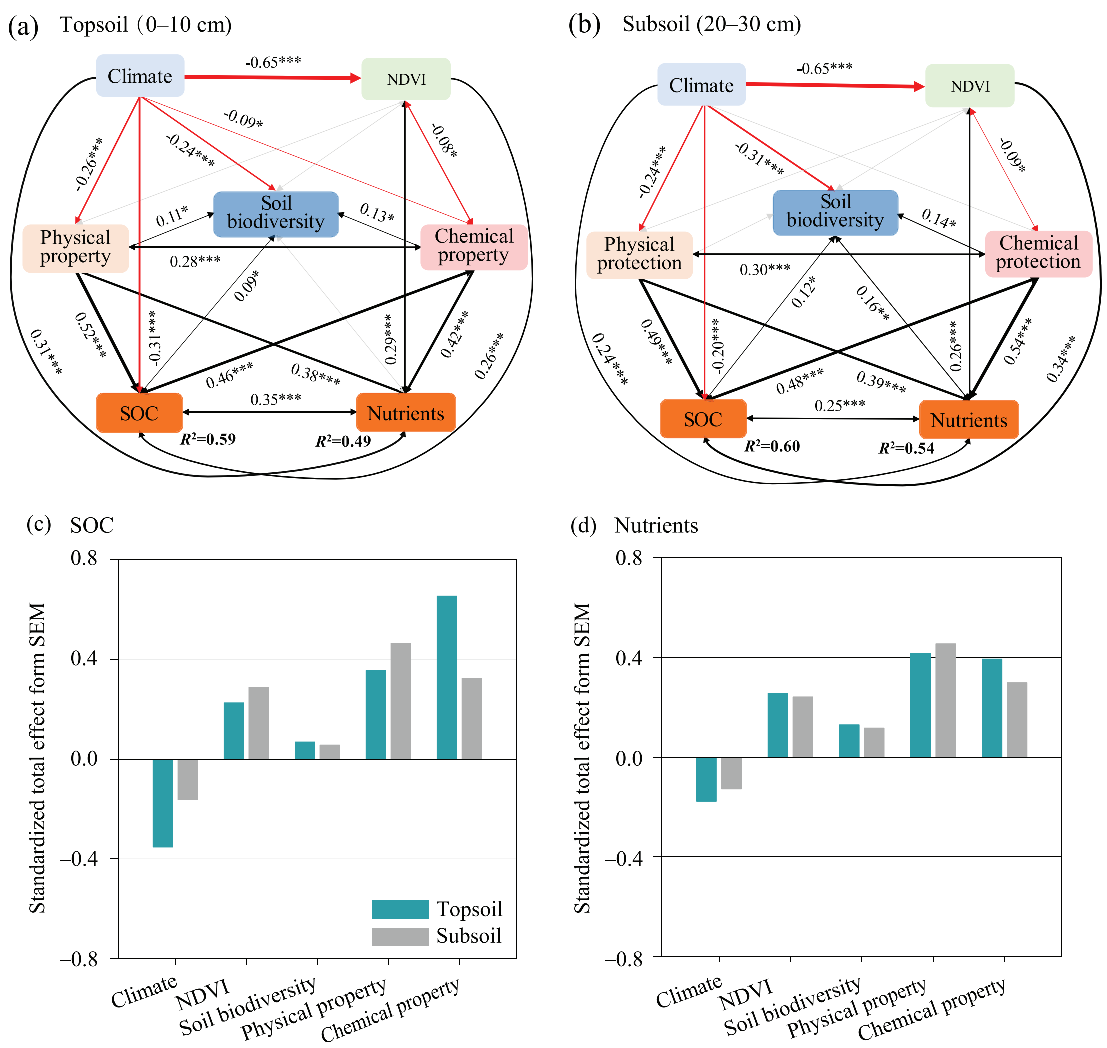

Figure 4. Structural equation models (SEMs) evaluating the direct and indirect effects on soil organic carbon (SOC) and nutrients across Australia ($n = 628$). SEMs for SOC and nutrients in the topsoil (a) and subsoil (b); Standardized total effects (direct plus indirect effects) derived from the SEMs for SOC (c) and nutrients (d). Black and red lines indicate positive and negative relationships, respectively; grey lines indicate the relationships are not significant at $P = 0.05$. Line thickness represents the magnitude of the path coefficient, and numbers adjacent to arrows are standardized path coefficients. Nutrients (indicators of available nitrogen, phosphorus, and potassium), climate (indicators of mean annual temperature and aridity index), soil biodiversity (indicators of bacteria and fungi), physical property (indicators of clay and silt), and chemical property (indicators of extractable iron and soil pH) are latent variables. The loading scores of indicators of each latent variable are shown in figure S7. NDVI, normalized difference vegetation index. $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

were the most important factor followed by chemical properties, soil biodiversity, climate, and productivity.

Results from SEMs showed strong connections among all the factors in both soil depths (figure 4; see the loading scores of each latent variable in figure S7). Our SEMs explained 59% (topsoil) and 60% (subsoil) of the spatial variation in SOC; and 49% (topsoil) and 54% (subsoil) of the variance in nutrient availability at the continental scale (figures 4(a) and (b)). In both soil depths, we found strong direct and indirect effects (e.g. through regulating soil biodiversity) of physico-chemical properties on SOC and nutrients (figures 4(a) and (b)). Consistent with results of BRTs, physico-chemical properties also fulfilled the most important role as indicated by the standardized total effects (figures 4(c) and (d)).

Further support for the importance of physico-chemical properties on SOC and nutrients was derived from BRTs and SEMs within different ecosystem types. The importance of the role of physico-chemical properties was evident in each ecosystem type (figures 5 and S8). In addition, consistent with the overall pattern at the continental scale (figures 4(a) and (b)), strong connections among these tested factors were found in each ecosystem type (figures S9–S12).

4. Discussion

4.1. Soil physico-chemical properties primarily controlled SOC and nutrients

In the present study, results showed that physico-chemical properties primarily predicted carbon storage and nutrient availability across Australia (figure 3). The role of climate, plant productivity, and soil biodiversity as drivers of SOC and nutrients has been well documented (Carvalhais *et al* 2014, Wagg *et al* 2014, Karmakar *et al* 2016), but they played a less important role compared to physico-chemical properties, even after accounting for interactive effects among variables (figure 4). In addition, the importance of physico-chemical properties was evident across soil depths and ecosystem types. However, there were some differences in the interrelationships among factors across ecosystem types, which were consistent with a recent study demonstrating the region-specific controls that impact SOC distribution across Australia (Viscarra Rossel *et al* 2019). For instance, strong relationships between climate and soil biodiversity were observed in cropland ecosystems; no significant relationship between plant productivity (as determined from NDVI) and nutrients was detected in arid ecosystems (figures S9–S12). Moreover, the relative influence of physical and chemical properties differed between the topsoil and subsoil in intensely human-managed croplands (figure 5), and this might be associated with farming practices (e.g. tillage and fertilizer inputs) (Six *et al* 2002b). Altogether, these results clearly indicate that physico-chemical properties, regardless of the soil depth and ecosystem type, have predominant impacts on SOC and nutrient availability across Australia, and strongly supports efforts to incorporate these mechanisms in carbon and nutrient cycling models (Abramoff *et al* 2018).

SOC and nutrients are regulated by both chemical and physical processes, and thus distinguishing between these processes can be arbitrary (Han *et al* 2016, Kramer and Chadwick 2018). However, our analysis provides insight into the relative influence of physical properties mediated by factors such as surface area, compared to chemical properties mediated via factors such as changes in chemical state of the soil system. Physical properties such as clay and silt particles are especially sensitive to flocculating influences, and the small size of clay and silt particles imbues them with a high specific surface area for SOC and nutrient sorption. Higher clay and silt contents are also generally associated with greater aggregate stability (Dagesse 2013). We also found that physical properties were particularly important for driving both SOC and nutrients in tropical and temperate ecosystems (figure 5).

Soil pH and extractable Fe, an essential micronutrient for organisms (Moreno-Jiménez *et al* 2019), were used to represent chemical properties. Soil pH indicates the overall chemical state of the soil system and dictates a number of geochemical gradients (Deng and Dixon 2007). DTPA-extractable Fe was correlated to ammonium oxalate extractable Fe (Geiger and Loeppert 1986); these forms of available Fe appear to be representative of short-range order minerals, which were correlated to SOC (Kramer and Chadwick 2018, Rasmussen *et al* 2018). Among all the drivers examined (including climate and biota), soil extractable Fe was found to exert the greatest effect on SOC at the continental scale ($r = 0.59$ and 0.52 in topsoil and subsoil, respectively; figure S2). Recently, Rasmussen *et al* (2018) also reported that some chemical factors (e.g. exchangeable calcium, and iron- and aluminum-oxyhydroxides) were stronger predictors of SOC storage than physical property of clay content.

4.2. Why are other factors less important?

Although physico-chemical properties primarily predicted SOC and nutrient availability across Australia, other factors should also be considered at an ecosystem-level. Climate, usually considered as one of the primary drivers (Karmakar *et al* 2016), had significant direct and indirect effects (figures 4(a) and (b)). However, compared to physico-chemical properties, climate had a less important role in predicting SOC or nutrients (figures 3–5). This suggests that climate usually has indirect effects through physico-chemical properties as shown in figure 4, such as the clear, strong relationship between A.I. and soil pH (Slessarev *et al* 2016) (figures S2–S6); clearly, the soil matrix ultimately controls the fate of SOC and nutrients (Doetterl *et al* 2015). In addition, the biotic factor of plant productivity is highly correlated to climate (figures 4(a) and (b)). Plant productivity is the main source of carbon input, and it has been well parameterized in models to predict SOC storage (Friedlingstein *et al* 2006). Our results showed that, in comparison with physico-chemical properties, plant productivity played a less important role. Therefore, our study refutes the paradigm that climate is the predominant factor predicting SOC and nutrients (Carvalhais *et al* 2014) at least across the Australian continent.

Soil biodiversity is also an indicator of soil quality in terms of its relationship to key functions such as soil structure maintenance and nutrients cycling. Thus, soil biodiversity is essential for ecosystem multifunctionality and sustainability (Wagg *et al* 2014, Delgado-Baquerizo *et al* 2016), and it has recently been incorporated into some carbon and nutrient cycling models (Louis *et al* 2016). However, soil biodiversity had a lower power to predict the spatial variation in SOC and nutrients compared to physico-chemical properties (figures 3–5). This could be partly related to the distinctive microbial diversity in Australian soils compared to the rest of the world because Australian soils are highly weathered (Eldridge *et al* 2018). The mechanisms linking to the low correlation between SOC or nutrients and soil biodiversity across the Australian continent need to be addressed in future studies.

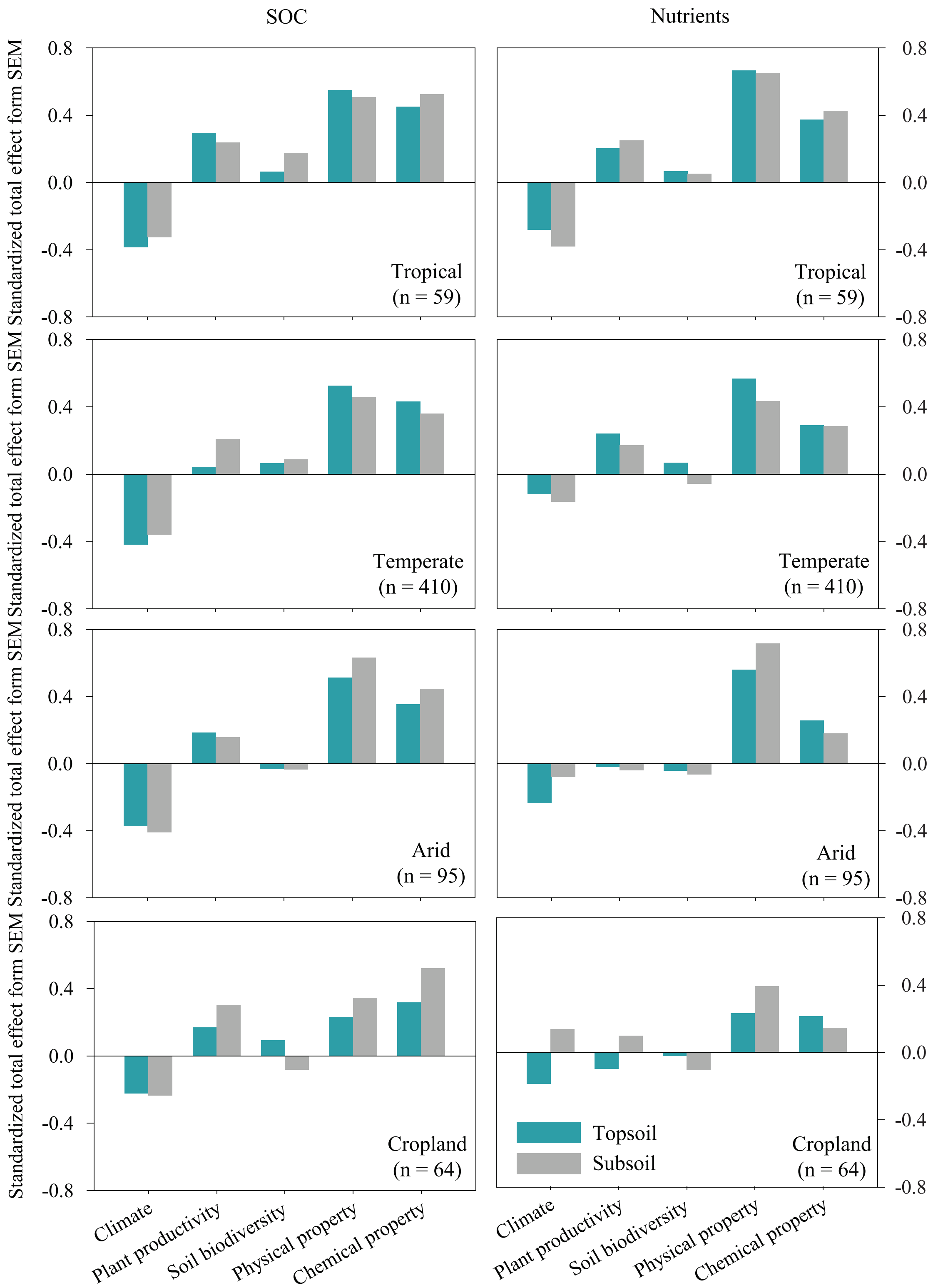

Figure 5. Standardized total effects (direct plus indirect effects) derived from structural equation models (SEMs) for soil organic carbon (SOC, left panel) and nutrients (right panel) in different ecosystem types. SEMs for each ecosystem are shown in supplementary figures S9–S12. The number in brackets indicates the sample size of each ecosystem type.

4.3. Uncertainties and outlook

Although our assessment was based on a large, continental database, the primary importance of soil physico-chemical properties in controlling SOC and nutrients might not extend to the global scale. Soils tend to be acidic, deeply weathered (Eldridge *et al* 2018), and depleted in nutrients and SOC (Lambers *et al* 2008) due to the lack of glacial disturbance on the ancient Australian landscape. This might also in part explain the particular importance of soil texture in predicting SOC in subsoil across the Australian continent, in contrast to its relatively low

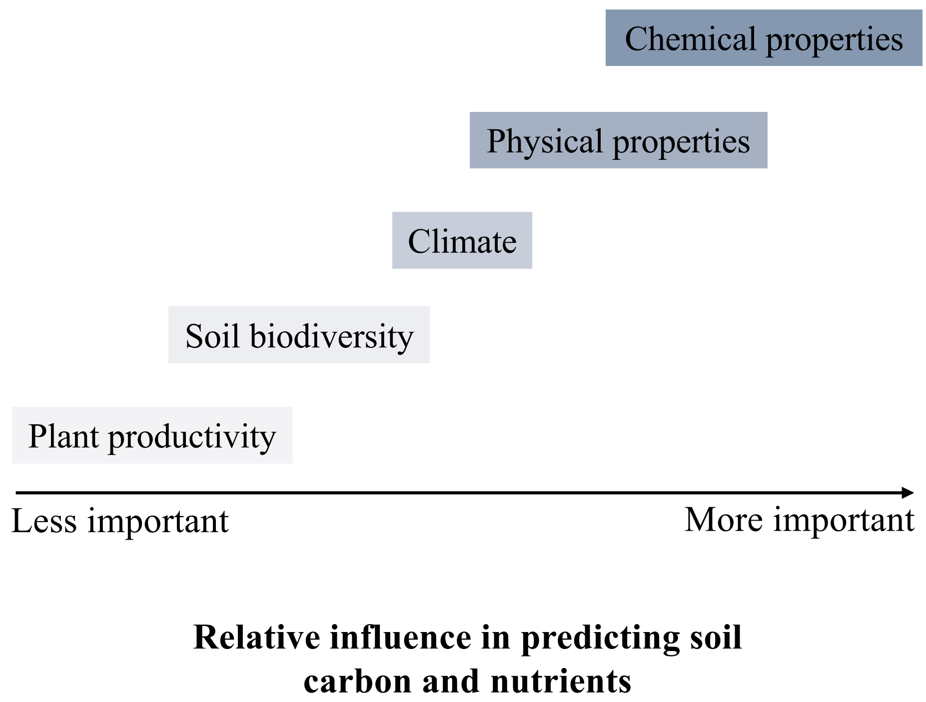

Figure 6. The relative importance of climate, plant productivity, soil biodiversity, physical properties and chemical properties in predicting soil organic carbon and nutrient availability.

explanatory power for soil carbon content in a larger study including younger soils in glaciated terrain (Rasmussen *et al* 2018). Thus, the global application of soil physico-chemical mechanisms in mediating SOC and nutrient availability is still an open question. More comprehensive data from other regions are deserved to gain further understanding on this issue. Secondly, some other important geochemical predictors (e.g. soil aggregates and mineralogy) of SOC and nutrients were not considered due to the limitation of this database. Although clay and silt particles are commonly associated with soil aggregation, direct linkages between soil aggregates and organic carbon will advance our understanding of soil physical properties regulating SOC in the future. Moreover, interestingly, significant relationships between SOC or nutrients and some other plant-available nutrient elements (e.g. calcium, aluminum, manganese, and zinc) were found. Because the mechanisms behind these relationships were unknown, they were not included in this continental-scale analysis. Finally, soil nutrients and biodiversity are highly variable over time. However, the data of soil nutrients and biodiversity at a typical site came from one single measurement, leading to uncertainties in evaluating the relative importance of soil biodiversity in controlling SOC and nutrient availability.

While all ecosystems demonstrated consistent importance of physico-chemical properties, some ecosystems were underrepresented. Most of the sites were distributed in temperate regions (~65%), dominated by forest and woodland, because there are many native forests in temperate regions, and they are considered important carbon sinks in Australia (Australia's State of the Forests Report 2018). Thus, these results suggest that physico-chemical properties are important for forest sustainability. Compared to temperate ecosystems, other ecosystems were relatively underrepresented (e.g. tropical ecosystem), leading to some uncertainties in these regions of the study area. Moreover, only ~2% of the total sampling sites were wetlands, leading to a knowledge gap for future research. Nevertheless, these findings throw new light on the leading role of soil physico-chemical properties at least from the 628 studied sites across the Australian continent, regardless of the soil depth and ecosystem type, and strengthens our knowledge of the mechanisms mediating soil carbon and nutrient availability.

5. Conclusions

Collectively, our results provide strong empirical evidence that soil physico-chemical properties play the most important role in predicting SOC and nutrient availability across Australia (figure 6). Our findings highlight that models predicting distributions and future trends of SOC and nutrients should combine principles of soil physico-chemical effects with soil biological processes (e.g. carbon dynamics and nutrient cycling) to rectify the inadequate representation of soil geochemistry in current global assessments (Tang and Riley 2015), at least in those deeply weathered areas where SOC and nutrients are relatively low like the Australian continent. Future work is needed to obtain the required global-scale data on soil geochemistry, and incorporate direct process-related controls in models of SOC and nutrient cycling. Although physico-chemical properties primarily predicted SOC and nutrient availability when accounting simultaneously for other drivers (climate, productivity, and soil biodiversity), how to effectively incorporate these physico-chemical factors into global biogeochemical models is still an open question.

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Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

J L and E P designed the study; J L analyzed the data with assistance from E P, J P, A B, and M N. J L wrote the first draft and all authors jointly revised the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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