Conversion from Upland to Paddy Field Intensifies Human Impacts on Element Behavior through Regolith

Huayong Wu, Xiaodong Song, Xiaorui Zhao, and Gan-Lin Zhang*

Despite many studies regarding the influence of the conversion from various types of land uses to paddy cultivation on soil change, little is known about how deep this influence may reach and what difference among elements may exist. To investigate the influence of the conversion from uplands to paddy fields on element behavior, we used mass-balance equations to quantify element loss and gain throughout the regoliths from surface to bedrock at the Red Soil Critical Zone Observatory in subtropical China. The studied regoliths, with a thickness of 7 to 8 m, are acidic and highly weathered and developed from Quaternary red clay underlain by sandstone bedrock. The conversion increased the loss of Fe by 44%, whereas it decreased the loss of Mn by 14% in the top 3 m within a short timescale (about 20 yr). Slight influences of the conversion were observed for Al, K, and Mg, but no noticeable influences were found for Ca, Na, Si, and P. The observable influence of the conversion reached depths of 3 m for Fe, Mn, and Al and 1 m for Mg and K. Below the 4-m depth, the influence was difficult to separate from the impacts of groundwater fluctuations. The lack of a noticeable influence on Ca and Na was mainly due to almost all of these elements having been depleted at the regolith–bedrock interface. Artificial flooding–drainage cycles and increases in fertilizer inputs in the paddy fields intensified the influence on element behavior via shifting the processes and sources of many elements in the regolith.

Abbreviations: RSCZO, Red Soil Critical Zone Observatory.

Chemical weathering during regolith formation is a fundamental land surface process that provides many essential nutrients and the primary habitat for life (Hahm et al., 2014; Arvin et al., 2017), affects atmospheric CO₂ concentrations (Walker and Hays, 1981; Berner et al., 1983; Kump et al., 2000; Dupré et al., 2003; Winnick and Maher, 2018), and modifies the Earth surface landforms (Heimsath et al., 1997, 2012). Both natural and anthropogenic forcings drive element inputs, translocation, transformation, and losses during regolith formation (Brantley et al., 2007; Brantley and Lebedeva, 2011; Richter and Yaalon, 2012; Richter et al., 2015; Song et al., 2018; Zhang et al., 2019). A state factor approach is commonly used to study soil or regolith formation as a result of natural environmental factors, including climate, organisms, parent material, topography, and time (Dokuchaev, [1883] 1967; Jenny, 1941). The role of each of these individual factors in governing regolith formation is being partially revealed using environmental gradients and the state factor equation (Ma et al., 2013; Dere et al., 2016; Liu et al., 2016; Buss et al., 2017; Chapela Lara et al., 2018). Human activities as the sixth factor of regolith formation have increased in frequency and magnitude in the Anthropocene (Yaalon and Yaron, 1966; Dudal, 2005; Richter et al., 2015). However, past studies have focused mainly on the upper 1 m or so surface soil but paid little attention to what may happen at depth. How human activities will transform element behavior in deep soil down to bedrock during regolith formation remains largely unknown.

Paddy fields are the largest anthropogenic wetlands on Earth and are intensively modified by anthropogenic forcings (Kögel-Knabner et al., 2010), having mainly developed from well-drained sloping uplands, alluvial plains, and poorly drained polder areas

© 2019 The Author(s). This is an open access article distributed under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
(Zhang and Gong, 2003). Land-use changes from various soil landscapes to paddy fields transformed the leaching and redox conditions due to artificial flooding–drainage cycles and thus would greatly perturb element behavior. Previous studies on conversion from uncultivated calcareous marine sediments to paddy fields presented gains of Al and Fe, no mass changes of K, and losses of all the other major elements through 1.2-m-deep soil profiles after 1000 yr of cultivation (Chen et al., 2011). Conversion of uplands to paddy fields derived from purple sandy shale, Quaternary red clay, or red sandstone caused significant decreases in total Fe within 300 yr of cultivation (Han and Zhang, 2013). Despite many studies regarding the influence of the conversion on soil changes, little is known about how deep such influence may reach. Regoliths are often several meters to tens of meters deep across the world (Richter and Markewitz, 1995; Befus et al., 2011; Goodfellow et al., 2014; Holbrook et al., 2014; St. Clair et al., 2015; Pelletier et al., 2016; Orlando et al., 2016; Wilford et al., 2016; Xu and Liu, 2017; Flinchum et al., 2018; Novitsky et al., 2018). The conversion of other soils to paddy soils may greatly influence element behavior beyond the routinely investigated solum when considering the porous and permeable regoliths (Wu et al., 2019). From previous studies (e.g., Huang et al., 2015, 2018) mostly focusing on the top 1 m, it is difficult to extrapolate the influence of the conversion on element behavior throughout the regolith. Deep sampling is clearly needed to study how deep the influence may reach in the regolith.

Red soils are widely distributed in tropical and subtropical areas of the world, particularly in South America, Central Africa, and South and Southeast Asia (He et al., 1983; Wilson et al., 2004). Red soils are mainly classified as Ultisols and Oxisols according to the USDA Soil Taxonomy (Soil Survey Staff, 2014) and as Acrisols, Alisols, and Ferralsols according to the Word Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Red soils cover an estimated 16% of the world’s ice-free land surface (NRCS, 2006) and 22.7% of China’s land surface (He et al., 1983). For the most part, red soils are highly weathered and inherently infertile (Wilson et al., 2004). Previous studies conducted in tropical and subtropical forests have provided important insights into element behavior during weathering of regoliths derived from basalt (Ma et al., 2007; Li et al., 2014; Jiang et al., 2018), granite (Murphy et al., 1998; White et al., 1998; Zhang et al., 2015; Liu et al., 2016; Buss et al., 2017; Chapela Lara et al., 2018), volcanics (Buss et al., 2013, 2017; Chapela Lara et al., 2018), and high-grade metamorphic charnockite (Hewawasam et al., 2013; Behrens et al., 2015). However, little is known about the depth and magnitude of the influence on element behavior by the conversion from uplands to paddy fields in tropical and subtropical cropland regoliths.

Our objectives in this study were to quantify the influence of the conversion from uplands to paddy fields on the behavior of major elements throughout the regolith. We hypothesized that the conversion of uplands to paddy fields would intensify the influence in magnitude and depth on element behavior mainly due to the artificial flooding–drainage cycles.

Materials and Methods

Site Description

The study area was located in the Red Soil Critical Zone Observatory (RSCZO) (28°14' N, 116°53' E) in Jiangxi Province, southern China (Song et al., 2019). The RSCZO is a 50-ha agricultural watershed, with elevations of 34 to 55 m and slope gradients of about 3 to 5°. The RSCZO has a humid subtropical monsoon climate with a mean annual temperature of 17.8°C, mean annual precipitation of 1795 mm, and mean annual evapotranspiration of 1229 mm (1954–1999). The land uses in the RSCZO are upland rainfed (44%), terraced irrigated paddy fields (20%), grape (Vitis vinifera L.) vineyards (10%), citrus (Citrus reticulate Blanco) orchards (6%), woodland (6%), and ponds and built land (6%). The rainfed uplands have a peanut (Arachis hypogaea) monocropping system. The growing season of peanut is usually from early April to early August. The paddy fields have a rice (Oryza sativa L.) double-cropping system. The growing season for early rice is usually from mid-April to mid-July. The growing season for late rice is usually from late July to mid-November. Paddy fields during rice growth are often submerged except for drained intervals needed for better production (usually several days) and a maturity period for the rice double-cropping system. The main fertilizers applied include urea, N–P–K compound fertilizer, KCl, and calcium magnesium phosphate fertilizer, according to a local fertilization survey. The RSCZO was derived from Quaternary red clay underlain by a layer of mixed clay and weathered Cretaceous sandstone. Quaternary red clay is mainly located in the lower and middle reaches of the Yangtze River in China (Hu et al., 2010). The regoliths at the RSCZO are acidic, highly weathered, and mainly clay loam to clay in texture (Wu et al., 2019). The Quaternary red clay consists of uniform red clay and reticulate red clay and is comprised predominantly of kaolinite, vermiculite–illite, and quartz, with minor Fe (oxy)hydroxides (goethite and hematite). The studied upland regolith with a thickness of 8.0 m consists of three layers including uniform red clay (0–0.7 m), reticulate red clay (0.7–6.2 m), and weathered sandstone (6.2–8.0 m). Similarly, the studied paddy field regolith with a thickness of 7.3 m consists of the uniform red clay (0–1.2 m) (morphologically transformed by paddy cultivation), reticulate red clay (1.2–5.2 m), and weathered sandstone (5.2–7.3 m). The studied paddy fields were converted from uplands about 20 yr ago, developed from the same parent materials (Quaternary red clay), and have a similar climate and topography.

Drilling and Sampling

Drilling was performed at the RSCZO by the local geological survey group of Jiangxi, using a hydraulic rotary drill (130-mm diameter) in April 2016. Due to the accessibility of the heavy equipment and elevation difference among land uses, the elevations of boreholes between the upland (50.3 m) and paddy field (47.5 m) were slightly different. The regolith cores and sandstone bedrock were collected from a depth of 1 to 10 m for Borehole 1 (upland) and from a depth of 1 to 8.5 m for Borehole 3 (paddy...
field. Core samples were divided into smaller intervals of about 20 cm in length. Samples from 0 to about 1 m were taken from hand-dug soil pits. Samples from the soil pits were collected at about 10-cm intervals. The regolith and sandstone bedrock were cleaned by removing the outer layer to prevent contamination during drilling.

Sample Preparation and Element Analysis

Regolith and sandstone samples were air dried, ground in an agate mortar with a pestle, and sieved through nylon mesh with a pore sizes of 0.15 mm. Concentrations of major elements were measured by inductively coupled plasma optical emission spectrometry (PerkinElmer Optima 8000) after lithium metaborate fusion in graphite crucibles at 950°C. Quality control of elements was through analysis of the Chinese soil standards GBW07405 and GBW07408. Measured data of the soil standards for the major elements were within 5% of the certified values.

Mass Transfer Calculations

To quantify the gain or loss of a given element in the regolith profile as a whole relative to the contribution from the parent material weathering, we calculated an integrated mass transfer coefficient \( \tau_{j,\text{int}} \) by weighting the mass transfer coefficient \( \tau_{j,i} \) at each sampling depth by the product of the bulk density \( (\rho) \) and the vertical distance \( (z) \) between measurements (Oh and Richter, 2005; Pett-Ridge et al., 2007; Chapela Lara et al., 2018):

\[
\tau_{j,\text{int}} = \sum \left( \frac{\tau_{j,b} \rho_b z_b}{\rho_t z_t} \right)
\]

where subscript \( b \) refers to values for individual sampling depths and the subscript \( t \) refers to values for the total profile. Bulk density was from Wu et al. (2019).

An element gain or loss across the entire regolith profile per unit area, \( m_{j,\text{flux}} \) (g cm\(^{-2}\)) can be estimated if we know the \( \tau_{j,\text{int}} \) of a given element and the bulk density of the bedrock \( (\rho_p = 2.34 \ \text{g cm}^{-3}) \):

\[
m_{j,\text{flux}} = \rho_p z_t C_{j,p} \tau_{j,\text{int}}
\]

Results

Element Concentrations

Total percentages (w/w) of CaO or Na\(_2\)O were similar, but those for K\(_2\)O or MgO were different between upland and paddy field regoliths (Fig. 1; Supplemental Tables S1 and S2). Calcium and Na were the lowest in content among the examined alkali and alkaline earth metals in both of the regoliths. In both the regoliths, CaO increased from, on average, <0.1% in the upper (uniform red clay) and middle (reticulate red clay) layers to 0.2% in the lower (weathered sandstone) layer, while Na\(_2\)O was, on average, 0.1% throughout the three layers. At the transition zone from regolith to bedrock in the upland soil, CaO and Na\(_2\)O abruptly increased from 0.2 to 5.9% and from 0.2 to 1.5%, respectively. Similar abrupt increases in CaO and Na\(_2\)O were also observed in the paddy field. Potassium and Mg were the most dominant alkali and alkaline earth metals for both of the regoliths (Fig. 1; Supplemental Tables S1 and S2). In the upland regolith, K\(_2\)O increased from, on average, 0.8% in the top two layers to 1.4% in the lower layer. In contrast, larger contents of K\(_2\)O were observed in the paddy field regolith, which increased from, on average, 1.1 or 1.2% in the top two layers to 2.5% in the lower layer. In the upland regolith, MgO increased from, on average, 0.4 or 0.5% in the top two layers to 0.9% in the lower layer. Compared with the upland regolith, slight increases in MgO in the upper and lower layers were found for the paddy field regolith.

Total percentages (w/w) of Al, Fe, or Mn on an oxide basis varied widely between upland and paddy field regoliths (Fig. 2; Supplemental Tables S1 and S2). In the upland regolith, Al, being the second-most abundant element among the examined elements, increased from, on average, 13% on an oxide basis in the upper and lower layers to 15% in the middle layer. However, in the paddy field regolith, Al\(_2\)O\(_3\) decreased from, on average, 15% in the upper and lower layers to 12% in the middle layer. In the upland regolith, Fe\(_2\)O\(_3\) decreased from, on average, 5.7% in the middle layer to 5.1% in the upper layer and 1.8% in the
lower layer. In the paddy field regolith, Fe₂O₃ increased from, on average, 4.4% in the middle layer to 6.1% in the upper layer and 4.8% in the lower layer. In the upland regolith, the average contents of MnO were no more than 0.2% in the three layers. In contrast, MnO in the upper and lower layers of the paddy field regolith were two to three times larger than those of the upland regolith.

In the upland regolith, Si, being the most abundant element except for O, increased from, on average, 67 to 75% on an oxide basis down through the three layers (Fig. 3; Supplemental Tables S1 and S2). However, in the paddy field regolith, SiO₂ decreased from, on average, 74% in the middle layer to 67% in the upper layer or 70% in the lower layer. In the upland regolith, P₂O₅ decreased from, on average, 0.09 to 0.05% down through the three layers (Fig. 3; Supplemental Tables S1 and S2). However, in the paddy field regolith, P decreased from, on average, 0.07% in the upper layer to 0.04% in the middle layer and then increased back to 0.07% in the lower layer.

In the upland regolith, Si, being the most abundant element except for O, increased from, on average, 67 to 75% on an oxide basis down through the three layers (Fig. 3; Supplemental Tables S1 and S2). However, in the paddy field regolith, SiO₂ decreased from, on average, 74% in the middle layer to 67% in the upper layer or 70% in the lower layer. In the upland regolith, P₂O₅ decreased from, on average, 0.09 to 0.05% down through the three layers (Fig. 3; Supplemental Tables S1 and S2). However, in the paddy field regolith, P decreased from, on average, 0.07% in the upper layer to 0.04% in the middle layer and then increased back to 0.07% in the lower layer.

Fig. 1. Total percentage by weight of (a) CaO and Na₂O and (b) MgO and K₂O of the regolith and bedrock in the upland and paddy field.

Total percentages (w/w) of TiO₂ were slightly different between upland and paddy field regoliths (Supplemental Table S1). In the upland regolith, TiO₂ decreased from, on average, 0.9% in the upper layer to 0.4% in the lower layer, while in the paddy field regolith, TiO₂ decreased from, on average, 1.1% in the upper layer to 0.7% in the lower layer.

Mass Transfer of Elements

Depletion profiles for Ca and Na were similar, but those for K and Mg were different between upland and paddy field regoliths (Fig. 4). Tau values ranged from −1.0 to −0.96 for Ca and from −0.99 to −0.88 for Na in both the upland and paddy field regoliths, which denotes that 96 to 100% of Ca and 88 to 99% of Na had been lost during regolith formation. The depletion of Ca was observed to be greater than that of Na. At the transition zone from regolith to bedrock, τ values for Ca and Na abruptly increased to around 0 within the 1.3-m depth interval. In the upland regolith, τ values for K increased from, on average, −0.84
in the upper layer to −0.45 in the lower layer. The paddy field presented a similar decreasing pattern to that of the upland but with, on average, 3 to 9% less loss of K in the three layers of the regolith than those of the upland. The decreasing pattern of Mg was similar to that of K in both of the regoliths. The paddy field regolith exhibited 13% greater loss of Mg in the lower layer than did the upland regolith. The depletion of Mg was found to be greater than that of K.

Element regolith profiles for Al, Fe, and Mn were different between upland and paddy field (Fig. 5). The upland regolith showed a depletion–enrichment profile for Al, whereas the paddy field presented a depletion profile. In the upland regolith, \( \tau \) values for Al increased from, on average, −0.44 in the upper layer to 0.27 in the lower layer. However, in the corresponding layers of the paddy field regolith, \( \tau \) values for Al increased from −0.46 to −0.15. Both of the regoliths showed depletion–enrichment profiles for Fe. The paddy field regolith exhibited, on average, 27% less gain of Fe in the middle layer than did the upland regolith. Both of the regoliths showed depletion profiles for Mn. The paddy field regolith presented, on average, 28 and 37% less loss of Mn in the upper and lower layers, respectively, than the same layers of the upland field regolith.

Depletion profiles for Si and P were observed to be slightly different between upland and paddy field regoliths (Fig. 6). The paddy field regolith presented, on average, 39% greater loss of Si in the lower layer than did upland regolith.

When integrated over the entire regolith using Eq. [2], the integrated mass transfer coefficient \( \tau_{\text{int}} \) showed that all the elements were depleted except Fe (Table 1). The absolute losses of Ca, Na, and Mg were similar, while the losses of Si, P, and K were slightly different between upland and paddy field regoliths. The paddy field regolith presented 22% greater loss of Al, 19% greater loss of Fe, but 22% less loss of Mn than the upland regolith.
When calculated as element gain or loss throughout the entire regolith profile per unit area using Eq. [3], the upland regolith lost 103 g cm$^{-2}$ of CaO throughout the 8.0-m depth, which corresponded to 16% of the total mass lost. The upland regolith lost 456 g cm$^{-2}$ of SiO$_2$ throughout the 8.0-m depth, comprising 70% of the total loss. The upland regolith lost 13 g cm$^{-2}$ of Al$_2$O$_3$ throughout the 8.0-m depth, which amounted to 2% of the total loss, whereas the paddy field regolith lost 47 g cm$^{-2}$ of Al$_2$O$_3$ throughout the 7.3-m depth, which accounted for 6% of the total loss. Both of the regoliths lost 0.3 to 0.9 g cm$^{-2}$ of MnO and P$_2$O$_5$, corresponding to no more than 0.1% of the total loss. In contrast, the paddy field regolith gained 3 g cm$^{-2}$ of Fe$_2$O$_3$ throughout the 7.3-m depth, which is 70% less than that of the upland field regolith throughout its 8.0-m depth.

Fig. 5. Mass transfer coefficient ($\tau_{ij}$) of (a) Al, (b) Fe, and (c) Mn throughout the regoliths in the upland and paddy field.

Fig. 6. Mass transfer coefficient ($\tau_{ij}$) of (a) Si and (b) P throughout the regoliths in the upland and paddy field.
Depths of Influence on Element Behavior of Land-Use Conversion

Depts of the noticeable influences were found to vary for different elements after the conversion of upland to paddy field (Table 2). The total porosities in the paddy field regolith ranged from 35 to 51%, while those in the upland regolith varied from 41 to 54% (Wu et al., 2019). When considering the permeability of the porous regoliths, artificial flooding after the conversion may greatly change the element translocation, transformation, and losses from the topsoils down to the bedrock surface. In reality, our previous study showed that the behavior of NO$_3^−$ and dissolved organic N were significantly different throughout the whole regolith between uplands and paddy fields (Wu et al., 2019). In contrast to dissolved species of elements, the total mass of elements may not be as sensitive as dissolved species. Our results showed that the influence of the conversion on Fe, Mn, and Al may reach the depth of 3 m (Fig. 2 and 5; Table 2). However, below 4 m the influence of the artificial flooding was difficult to separate from that generated by the groundwater table fluctuation, usually between 4 and 6 m (Wu et al., 2019). The influence on K and Mg may reach the depth of 1 m (Fig. 1 and 4; Table 2). The land-use change exhibited no notable influences on Si, Ca, and Na in the top 3 m. Because of very low contents and relatively large variations of P (Fig. 3), the depth of the slight influence of the conversion for this element was not easily identified in this work. Taken together, our results indicate that the influence of the conversion on the behavior of many elements greatly exceeded the top 1-m soils and may extend into the whole regolith.

Magnitude of the Influence of Land-Use Conversion

The net mass change in many major elements was different between upland and paddy field whether looking at the whole regolith or the top 3 m (Tables 1 and 2). As mentioned above, comparison of the net changes in the top 3 m would facilitate separation of the influences of the conversion from those of groundwater. The conversion was observed to substantially change the losses or gains of Fe and Mn and slightly change that of Al in the top 3 m.

For Fe, both of the upland and paddy field regoliths exhibited depletion–enrichment profiles and net gains. A similar type of Fe profile was also found in the regoliths derived from granitic gneiss and phyllite in forests in the southeastern United States (Oh and Richter, 2005) and from granite in forests in subtropical China (Liu et al., 2016). Greater enrichment of Fe at depth in the reticulate red clay in the upland regolith suggests that Fe may have accumulated during regolith formation in the Quaternary period. It has been hypothesized that this layer had mostly originated from Quaternary alluvial sediments and was formed during the last interglacial period with under a hot, wet climate (Li et al., 2008; Hu et al., 2010, 2015). Under the conditions of the paleoclimate,
Fe may be reduced, transported, and re-oxidized at depth. This inference is also supported by the noticeable redox record of a net-like pattern with white veins in the red-brown matrix in this layer (Zhao et al., 2019). Large net gains of Fe did not likely result from atmospheric deposition but may be ascribed to inputs from the alluvial sediments (Hu et al., 2010) and removals in the depletion zone of the uniform red clay under an intensive erosion condition (Zhao et al., 2013).

In contrast to rainfed uplands, the artificial flooding in the paddy fields caused strong leaching and reducing conditions. The conversion was found to cause the loss of Fe by 44% in the top 3 m (Table 1). This was largely attributed to the reduction of ferric Fe in Fe (oxy)hydroxides and clay and thus downward translocation of ferrous Fe under the artificial flooding and anoxic conditions. These were supported by the Eh and pH values of the acidic paddy soils (Zhao et al., 2013). The difference may be due to more additions of Mn (Tipping, 2005; Li et al., 2006; Ščančar and Milačič, 2006; Huang et al., 2019), which is supported by the studies of Al speciation in soils across a long-term timescale.

For Al, the upland regolith exhibited a depletion–enrichment profile, whereas the paddy field regolith presented a depletion profile. The conversion was observed to cause a slight increase in the loss of Al in the top 3 m, which was probably due to the decrease in the vertical eluviation of Al, possibly in the forms of soluble Al, Al (oxy)hydroxides, and clay under the artificial flooding. The soluble Al would be ubiquitously present in the acidic paddy soils with pH values ranging from 4.6 to 5.6 in this study (Wu et al., 2019), which is supported by the studies of Al speciation in soils (Tipping, 2005; Li et al., 2006; Ščančar and Milačič, 2006; Huang et al., 2014).

Additionally, desilication was observed to be the most predominant pedogenic process in this work. No notable influence of the conversion was observed for Si in the top 3 m, whereas the differences between the two regoliths were mainly observed below 4 m. Alkali and alkaline earth metals (mainly Ca) were depleted in great amounts following desilication. The conversion led to no notable influences on the net losses of Ca and Na (Table 2), which were largely due to the high weathering degree of the regoliths and high mobility of these elements. Nearly all the Ca and Na were depleted at the regolith–bedrock interface, which can be thought of as the bedrock weathering front. The conversion was observed to cause a slight decrease in the loss of Mg and K in the top 1 m (Fig. 1 and 4), which was probably due to more additions of fertilizers such as N–P–K compound fertilizer and calcium magnesium phosphate fertilizer to paddy fields with a rice double-cropping system. Furthermore, Mg and K were abruptly depleted at the weathering front and then progressively depleted from the weathered sandstone to the reticulate red clay. This suggests that Mg- and K-bearing minerals were relatively resistant to weathering or that Mg and K were transformed into secondary clay minerals such as vermiculite or illite as the main 2:1 layered clay mineral in the regolith. In contrast to Ca and Na, Mg may be incorporated into the crystal lattice of vermiculite or illite by isomorphous substitution of Al, and Mg and K are the main interlayer cations for these minerals and may greatly be fixed (Huang et al., 2011).

Despite no observable influence of the conversion on P, increases of P from subsurface to surface in the uniform red clay of both regoliths clearly indicated the inputs of fertilizer P (Fig. 3 and 6). Consequently, fertilizer inputs at the surface replenished the sources of P generated from chemical weathering at depth.

**Conclusions**

Conversion from upland to paddy field exhibited substantial influence on the processes of Fe and Mn, slight influence on Al, K, and Mg, but no noticeable influence on Ca, Na, Si, and P in the top 3 m within a short timescale (about 20 yr). The observed influence of the conversion reached depths of 3 m for Fe, Mn, and Al and 1 m for K and Mg. The influences were difficult to separate from those originating from groundwater fluctuations below 4 m. Artificial flooding and drainage cycles and increases in fertilizer inputs intensified the influences via shifting the processes and sources of elements throughout the regoliths.

**Acknowledgments**

This work was funded by the National Natural Science Foundation of China (41571130051; 41977003; 41501228), and the Frontier Program of the Institute of Soil Science, Chinese Academy of Sciences (ISSASIP1625).

**Supplemental Material**

Supplemental material includes (i) data on total element weight percentages (% w/w) on an oxide basis of the regolith and bedrock in the upland (Supplemental Table S1) and in the paddy field (Supplemental Table S2), and (ii) photographs of weathered sandstone samples showing Mn oxide nodules or coatings from upland and paddy field regoliths at depths of 740 to 760 and 670 to 700 cm, respectively (Supplemental Fig. S1).
References


VZJ | Advancing Critical Zone Science p. 9 of 10