The Three Gorges Dam accelerates acidification of upland soils

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Brief Communication

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Abstract

Large hydroelectric dams have provided extensive benefits in supporting human socio-economic development but their environmental footprint has come under increasing scrutiny. Lack of continued long-term monitoring of the environment remains a key constraint to the understanding of the correlation between dam operation and the environmental changes. Here we assess the impact of the Three Gorges Dam on upland soils in the reservoir area. By tracking the changing of pH value, a general indicator of soil health, over a period spanning nearly three decades before and after the dam construction, we observe continuous pH decline evidencing ongoing soil acidification. In addition to the intensive proton supply from applied fertilizers, the presence of the megaproject is believed to be a major driver of the accelerated soil acidification. Further analysis reveals that the shifts of microclimatic conditions as a result of the dam leads to the enhanced decomposition of organic species and the concomitant loss of exchangeable base cations, which contribute additional protons to soil and reduce soil acid-buffering capacity, respectively. Our findings identify the ecological impacts of the world's largest dam and suggest the urgency to initiate environmental protection measures for improved sustainability.

Main Text

The Three Gorges Dam (TGD) on the Yangtze River is the largest hydraulic engineering project in the world[1-3], and its impact on the health of ecosystems has been a subject of intense debate at all levels, including climate, eco-environment and social economy[4-7]. No matter what the results of these debates are, it is commonly accepted that large dams (height >15 m or volume > 3 million m^3) in different areas and climatic zones often affect the microclimate during their building and service life span[8-11]. However, the environmental impacts of large dams (e.g. TGD) in the context of sustainability remain controversial.

One viewpoint underscores that the presence of TGD causes negative environmental impacts such as amplification of pollutant (e.g. methyl mercury) transport into tributaries[12-14], and disturbances to soil organic matter[11,15] due to the changes in hydrological regime and inundation[16], as well as resettlement and construction of the dam[7]. Another viewpoint argues that natural variation in the environment is more significant than the dam effects[17]. Here, the scientific stance is that TDG provides many benefits for environmental improvement such as flood control[18], facilitation of sediment deposition that leads to cleaner water in the reservoir[7].

There is no doubt that the Three Gorges Project (TGP) eco-environmental impacts are very complicated, with some having long-term consequence. Accordingly, the TGP Ecological and Environmental Monitoring System (TGPEEMS), which was initiated in 1996, covers: water resources, environmental protection, agriculture, forestry, meteorology, health, geology and mineral resources, earthquake risk, and communications[7]. To date, there is relatively clear understanding and consensus on the impacts of the TGP on hydrology[19], aquatic environment[20], fisheries[21], biodiversity, and the water level fluctuation zone[22]. However, there is less analysis and interpretation of the impacts of the TGP for upland soil quality

despite some parameters such as soil fertility being included in TGPEEMS. To the best of our knowledge, the undetermined consequences of the dam construction on soil quality in the uplands in the TGD reservoir area, has been overlooked, largely because of the lack of analysis and interpretation of long-term *in-situ* data collected before and after TGD construction.

Agricultural lands in the TGD reservoir area, with only 0.07 ha/person, are predominantly located in the surrounding mountainous region[7]. Due to soil erosion and the widespread use of fertilizers with high application rates, there is a critical need to assess if soil quality in the uplands is being degraded. Soil acidity, represented by soil pH, is a widely applied metric for soil quality, and its change affects biogeochemical cycles, and, subsequently, soil fertility and soil ecosystem health[23]. A survey in 2017 indicates that the pH of TGD upland soils (75 samples from altitudes between 200 and 1700 m) ranged from 3.66 to 7.77. Importantly, the pH of 49% of the sampling sites was < 5.5 which is often used as the threshold value of healthy and sustainable soils[24]. Such data suggest that soil acidification in the TGD uplands has entered an alarming stage, and there is an urgent need for rehabilitation.

In this context, we have performed a systematic study of upland soil to extract insight into the acidification dynamics and better inform the policy makers. Although the experimental watershed and the control watershed (Supplementary Fig. 1) have similar geographical characteristics, crop types and fertilizer management methods, the soil pH in the experimental watershed decreased relatively faster than that in the control watershed. Specifically, the average soil pH in the experimental watershed declined from 6.56 in 2003 to 5.62 in 2018. This represents a difference in pH (DpH) = −0.94 over the 16-year period. This equates to an 8.7-fold increase in acidity on the basis of the concentration of protons, and is likely to have a substantial impact on plant growth[25]. However, soil pH in the control watershed exhibited a DpH = -0.32, equivalent to a 2.1-fold increase in acidity between 2003 and 2018 (Fig. 1a). Historically, before dam construction, the average soil pH of the TGRA was around 6.80 (1990–2002). The average value from 2003 to 2018, spanning pre- and post-dam construction was 6.11. Importantly, our analysis reveals that the decrease in soil pH after dam construction is faster than that before (Fig. 1b).

We also monitored the latitude dependence of soil. Over the past 16 years, changes in soil pH for the different altitude categories in the experimental watershed are as follows: a decrease from 7.11 to 5.95 (DpH = −1.16) for low (200-600 m) altitudes; 6.43 to 5.51 (DpH = −0.92) for intermediate (600–900 m) altitudes; and 6.13 to 5.31 (DpH = −0.82) for high (900–1200 m) altitudes. Therefore, the reduction in soil pH was most pronounced at low altitudes (Fig. 1c).

To determine why the reduction in soil pH was accelerated after construction of the TGD, we conducted a controlled experiment to assess the change in soil pH under simulated microclimate conditions before and after dam construction. The changed soil pH was the difference between the original soil pH and the average of soil pH provided by the three most recent samples. Our results show that soil pH decreased both before (DpH = 1.08) and after (DpH = 1.17) dam constructions at low altitude (200 m). Similarly, the decrease in pH after dam construction (DpH = -1.09) at intermediate altitude (700 m) was also slightly greater than that before (DpH = -1.04) (Fig. 1d&e).

To explore the reasons accelerating soil acidification, we tested the contributions of acid deposition[26], soil nitrification and NH_4^+ fertilizer nitrification[27], organic matter decomposition[28] and exchangeable base cations loss[28] to changes in soil pH because they are known as key factors driving soil acidification[25,29]. Firstly, the contribution of acid deposition on decreasing soil pH can be excluded. This is because the average measured rainwater pH in the experimental area over the sampling period was 6.77 (Supplementary Table 1), suggesting that the acidification due to rainfall was negligible.

Then for insight into the soil nitrification (actually soil nitrification based on two substrates: soil itself and NH_4^+ fertilizer in the soil), we determined the nitrifying microorganisms in the experimental watershed because nitrification in soil is driven by microorganisms[30], with the extent depending on the microorganisms involved. *Nitrososphaeraceae*[31], *Nitrospiraceae*[32] and *Nitrosomonadaceae*[33] are the main families of nitrifying microorganisms present in the experimental watershed. The relative abundances of nitrifying microorganisms increased from 2005 to 2019 (Supplementary Fig. 2a). The abundances of nitrifying microorganisms had significant logarithmic or linear relationships with soil pH values (Supplementary Fig. 2b&c), implying that the decrease in soil pH with time was related to soil nitrification in the experimental watershed.

To quantify the contribution of NH_4^+ fertilizer nitrification to soil acidity, we investigated the effect of fertilizer applications on changes in soil pH based on the simulated 'NH_4^+ fertilizer' and 'no NH_4^+ fertilizer' treatments. Results show that the DDpH contributions (i.e., the differences between the DpH values with and without fertilizers) of fertilizers after dam construction (+0.03 at low altitude and +0.07 at intermediate altitude) were similar to those before the dam construction (+0.05 at low altitude and +0.06 at intermediate altitude) (Fig. 1d&e). This implies that the contributions of fertilizers before and after TGD construction are similar. These simulated results further suggest that the accelerated decline in soil pH in the uplands of the TGD watershed is attributable to the dam construction.

Fig. 1 The changes in soil pH. **(a)** Water level of the Three Gorges Dam from 2003 to 2018 and the overall change of soil average pH in the experimental and control watersheds. **(b)** The soil pH in the experimental watershed from 1990 to 2018 (n=970). **(c)** The overall change in pH at different altitudes in the experimental watershed from 2003 to 2018. The green, blue, and red lines indicate the trend in soil pH change at low altitude (200-600 m), intermediate altitude (600-900 m) and high altitude (900-1200 m) respectively. **(d)** The changes in soil pH under simulated local microclimatic conditions before dam construction. **(e)** The changes in soil pH under simulated local microclimatic conditions after dam construction [F in (d) and (e) refers to ammonium sulfate fertilizer, 330 and 330 kg/N/ha for low and intermediate altitudes, respectively].

Changes in soil pH due to soil organic matter (SOM) decomposition were tested in the experimental watershed through the investigation of organic matter decomposers. The phylum *Ascomycota*[34], genera *Bacillus*[35], *Streptomyces*[36] and *Pseudomonas*[37] which have been proved to be able to decompose SOM were quantified. Overall, the SOM-decomposers increased substantially in relative abundances from 2005

to 2019 (Supplementary Fig. 2a). Significant logarithmic or linear relationships between soil pH and the abundances of SOM-decomposers were observed (Supplementary Fig. 2b&c), implying that the decline in soil pH was directly associated with SOM decomposition.

Finally, we focused on the effects of exchangeable base cations on shifts in soil pH. Given the pH is <6.2, the acidification process is buffered by base cations, such as exchangeable Ca^{2+} and Mg^{2+} [38]. The depletion of base cations (Ca^{2+}, Mg^{2+} and Na^{+}) occurred in the experimental watershed after dam construction (Supplementary Fig. 3), resulting in a decline of acid-buffering capacity. There were good linear relationships between the soil pH values and the exchangeable Ca^{2+}, Mg^{2+} and Na^{+} concentrations in soils (Fig. 2). These results indicate that the decline in soil pH was partly because of the decreased acid-buffering capacity.

Fig. 2 Relationships between changes in soil pH (ΔpH) and the changes in soil base cations (**a.** ΔCa^{2+}, **b.** ΔMg^{2+} and **c.** ΔNa^{+}). Change in soil base cations refers to the difference between base cations in a given year and those in the first year (2004) after reservoir impoundment. Green, blue and red lines indicate the trends in the exchangeable base cation content at low, intermediate and high altitudes, respectively. R^2 values indicate the proportion of variance explained by each variable. *p* is the significance level.

To explain why the abundances of nitrifying microorganisms and SOM-decomposers in upland soils increased with time after the TGD construction, we investigated their relations with environmental factors. The change in environmental conditions, and especially local microclimate conditions, was one of the most important factors driving the change in microbial populations[39,40]. It has been previously reported that the microclimate (evaporation, relative humidity, soil temperature and precipitation) in the experimental watershed changed after TGD construction[6]. Thus, these four microclimatic factors were selected to conduct redundancy analyses (RDA) with nitrifying microorganisms and SOM-decomposers (Supplementary Fig. 4). Our results demonstrate, unambiguously, that the change in the microclimate for the experimental watershed has a substantial promoting effect on the nitrifying microorganisms and SOM-decomposers.

Why did the major base cations decrease continuously year by year? We investigated changes in the soil particle size after the construction of the TGD (Fig. 3). After a long period of erosion, soil particle size changed in the experimental watershed, with the average proportions of silt and clay (from 2004 to 2018) decreasing from 41.5% to 32.4% and 17.3% to 15.7%, respectively, whereas the average proportion of sand increased from 41.5% to 52.0% (Fig. 3). There was a significant negative correlation between soil sand content and exchangeable base cations, and a significant positive correlation between soil clay or silt content, and exchangeable base cations ($p < 0.05$) (Supplementary Table 2). Here, it is likely that the reduction in soil clay content in the experimental watershed reduced the content of exchangeable base cations since the adsorbed cations are carried away with the eroded soil particles[41,42]. On the other hand, precipitation directly caused base cations to migrate with water, since they are solubilized in the more acidic runoff.

Fig. 3 The change in soil particles size composition in the experimental watershed from 2005 to 2018. Change in soil particle size composition refers to the difference between particle size composition in a given year and that in the first year (2004).

Partial least squares path modeling (PLS-PM) was conducted to integrate the time series in processes and changes in soil pH (Fig. 4a). Dam-induced water level fluctuation was the dominant factor indirectly affecting the change in microclimate (path coefficient = -0.80). For the nitrifying microorganisms and the SOM-decomposers, the change in the local microclimate had negative effects. The losses of exchangeable base cations were directly due to the shifts of local microclimate conditions. The decrease in soil pH was directly affected by nitrifying microorganisms (path coefficient = -0.28), SOM-decomposers (path coefficient = -0.15), soil exchangeable base cations (path coefficient = 0.98) and fertilizer application (path coefficient = -0.31). It is apparent from this analysis that the water level fluctuation caused by the construction of the TGD indirectly contributed to the changes in soil pH in the experimental watershed. An increase in water level results in a lower soil pH (DpH = 0.69, the difference in the average soil pH spanning before and after damming).

Fig. 4. Schematic of the contributions to the decline in soil pH and corresponding mechanisms. (a) PLS-PM depicting the pathway of water-level change acting on soil pH in the experimental watershed affected by the TGD. Meteorological parameters include evaporation, relative humidity, soil temperature and precipitation; Nitrifying microorganisms include genera *Nitrosomonadaceae*, *Nitrososphaeraceae* and *Nitrospiraceae*; SOM-decomposer microorganisms (SOM decomposer microorganisms) include phylum *Ascomycota*, genus *Bacillus*, *Streptomyces* and *Pseudomonas*; Soil exchangeable base cations comprise Ca^{2+}, Mg^{2+}, Na^{+}. The width of the arrows indicates the strength of the direct effect, and the wider the arrow, the greater the coefficient. Solid lines indicate positive effects and dashed lines indicate negative effects. **(b)** The main processes leading to soil acidification in the TGRA.

This study indicates that large dam construction may indirectly disturb upland soil quality in the dam watershed through facilitating H^{+} accumulation and reducing soil pH buffering capacity. The main processes causing soil acidification have been revealed by our work (Fig. 4b). (1) The presence of TGD changes the microclimate including evaporation, relative humidity, soil temperature and precipitation in the experimental watershed. (2) The use of NH_4^{+} fertilizer provides substrates for nitrifying microorganisms and SOM-decomposers and these drive the processes of soil nitrification and SOM decomposition. (3) The change of microclimate in the experimental watershed promotes an increase in the abundances of both nitrifying microorganisms and SOM-decomposers, which promotes soil nitrification and SOM decomposition (Supplementary Fig. 5 shows the changes in SOM over time). (4) Erosion decreases the soil clay content and leads to the loss of soil exchangeable base cations, resulting in a decline in soil acid-buffering capacity.

Mitigation of soil acidification for improving soil ecosystem health for sustainability is urgently needed in the uplands of TGRA. This urgency underscores the need for a soil protection plan to alleviate soil acidification using easy-operation, low-cost and effective technologies. Ecological agricultural engineering that manifests long-term dual benefits – reductions of nutrient and soil losses, and improvements to soil quality, is encouraged[43]. For a long term perspective, we appeal to a national policy to support the continued running of the TGPEEMS, and the inclusion of soil quality and soil health parameters in the TGPEEMS for a comprehensive understanding and assessment of the environmental consequences of TGP. To maintain the long-term sustainability of the uplands of TGRA, a targeted land use policy promoting a reduction of steep slope farming and conversion to forest and grassland is encouraged. Our findings, although based on the TGRA, are useful for policy making and regular management for the upland soil ecosystems of other large reservoirs worldwide.

Declarations

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Author contributions:

Y.W, H.L., L.X., and R.S conceived and designed the project; H.L., S.W., P. S., M.G., Y.X., L.X., X.Z., and Y.W. carried out the experiments; H.L. and S.W. performed computational studies; Y. W., H.L., J.L., P.K., R.X., R.S. and A.C. wrote discussed the results and structured and wrote the manuscript.

Ethics declarations:

Competing Interests. The authors declare no competing interests.

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Figures

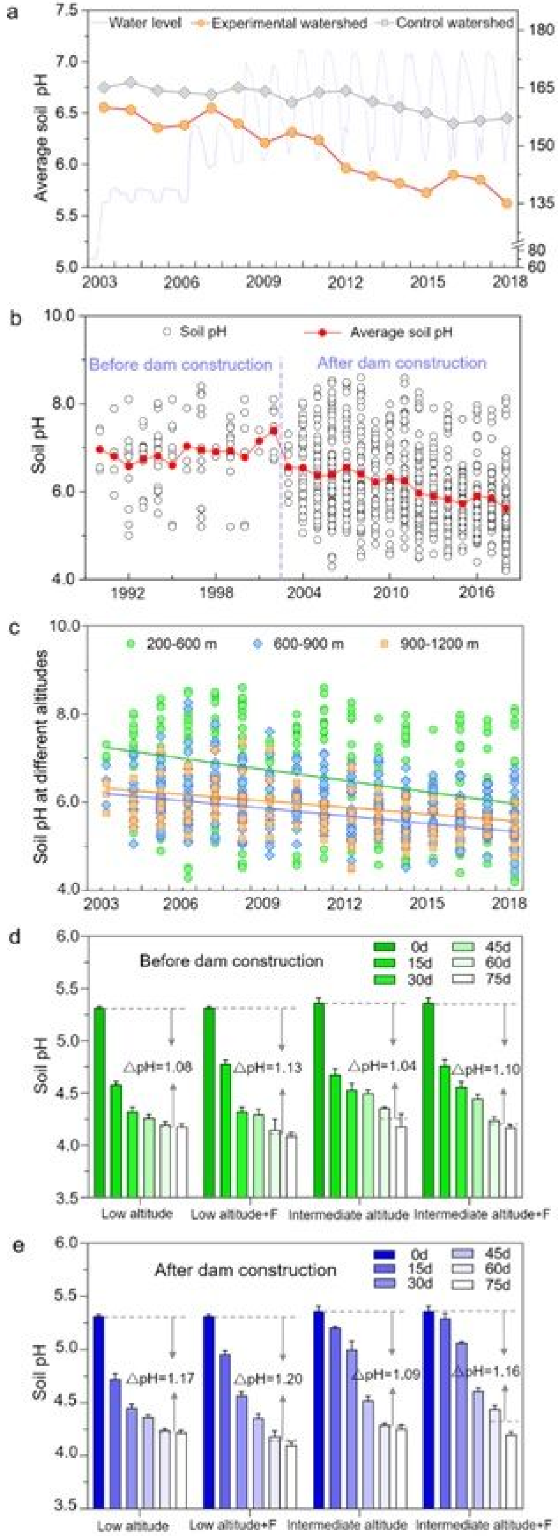

Figure 1

The changes in soil pH. (a) Water level of the Three Gorges Dam from 2003 to 2018 and the overall change of soil average pH in the experimental and control watersheds. (b) The soil pH in the experimental watershed from 1990 to 2018 (n=970). (c) The overall change in pH at different altitudes in the experimental watershed from 2003 to 2018. The green, blue, and red lines indicate the trend in soil pH change at low altitude (200-600 m), intermediate altitude (600-900 m) and high altitude (900-1200 m)

respectively. (d) The changes in soil pH under simulated local microclimatic conditions before dam construction. (e) The changes in soil pH under simulated local microclimatic conditions after dam construction [F in (d) and (e) refers to ammonium sulfate fertilizer, 330 and 330 kg/N/ha for low and intermediate altitudes, respectively].

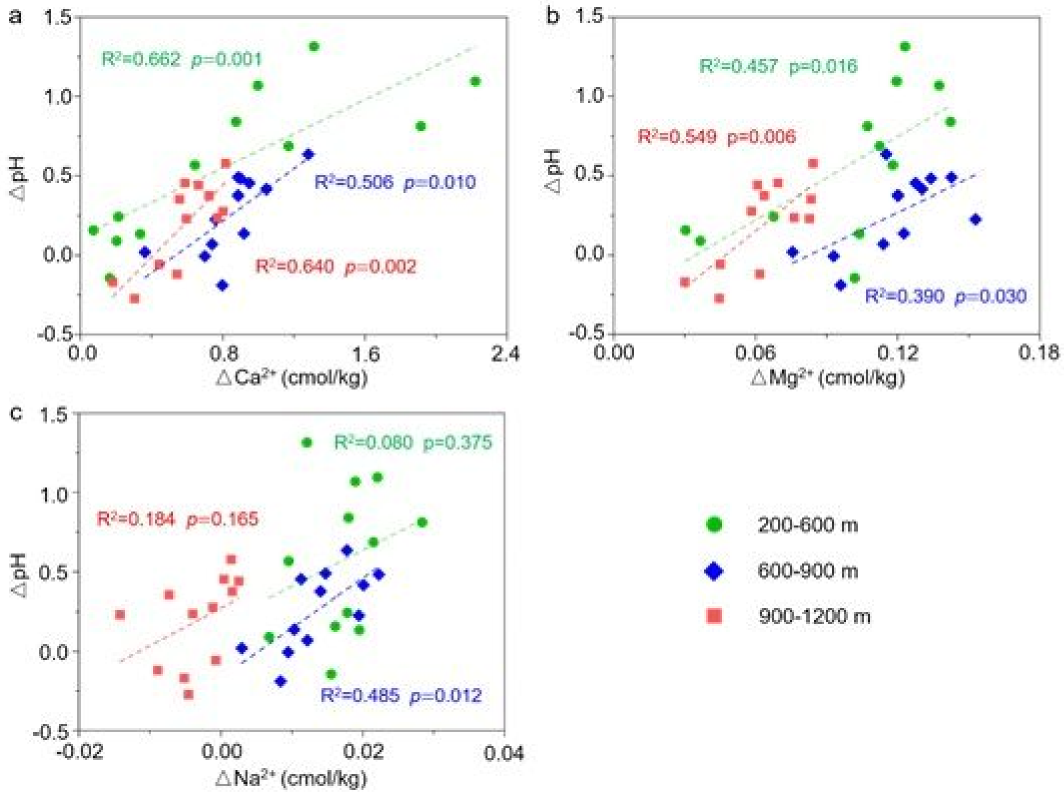

Figure 2

Relationships between changes in soil pH (ΔpH) and the changes in soil base cations (a. ΔCa2+, b. ΔMg2+ and c. ΔNa+). Change in soil base cations refers to the difference between base cations in a given year and those in the first year (2004) after reservoir impoundment. Green, blue and red lines indicate the trends in the exchangeable base cation content at low, intermediate and high altitudes, respectively. R2 values indicate the proportion of variance explained by each variable. p is the significance level.

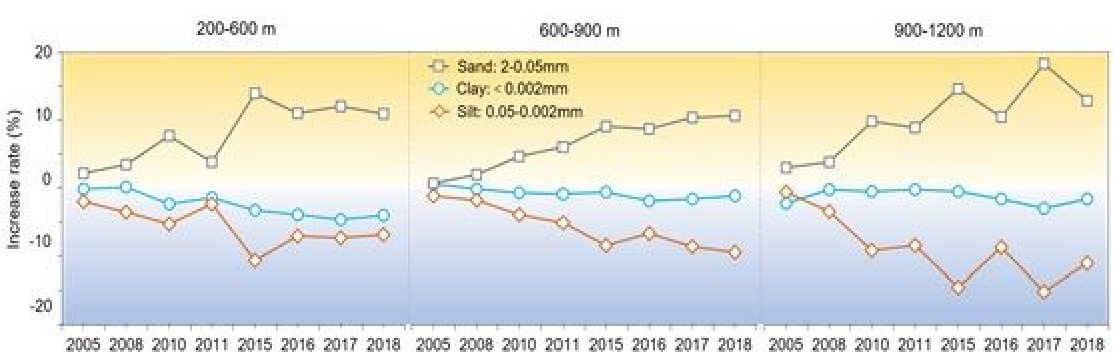

Figure 3

The change in soil particles size composition in the experimental watershed from 2005 to 2018. Change in soil particle size composition refers to the difference between particle size composition in a given year and that in the first year (2004).

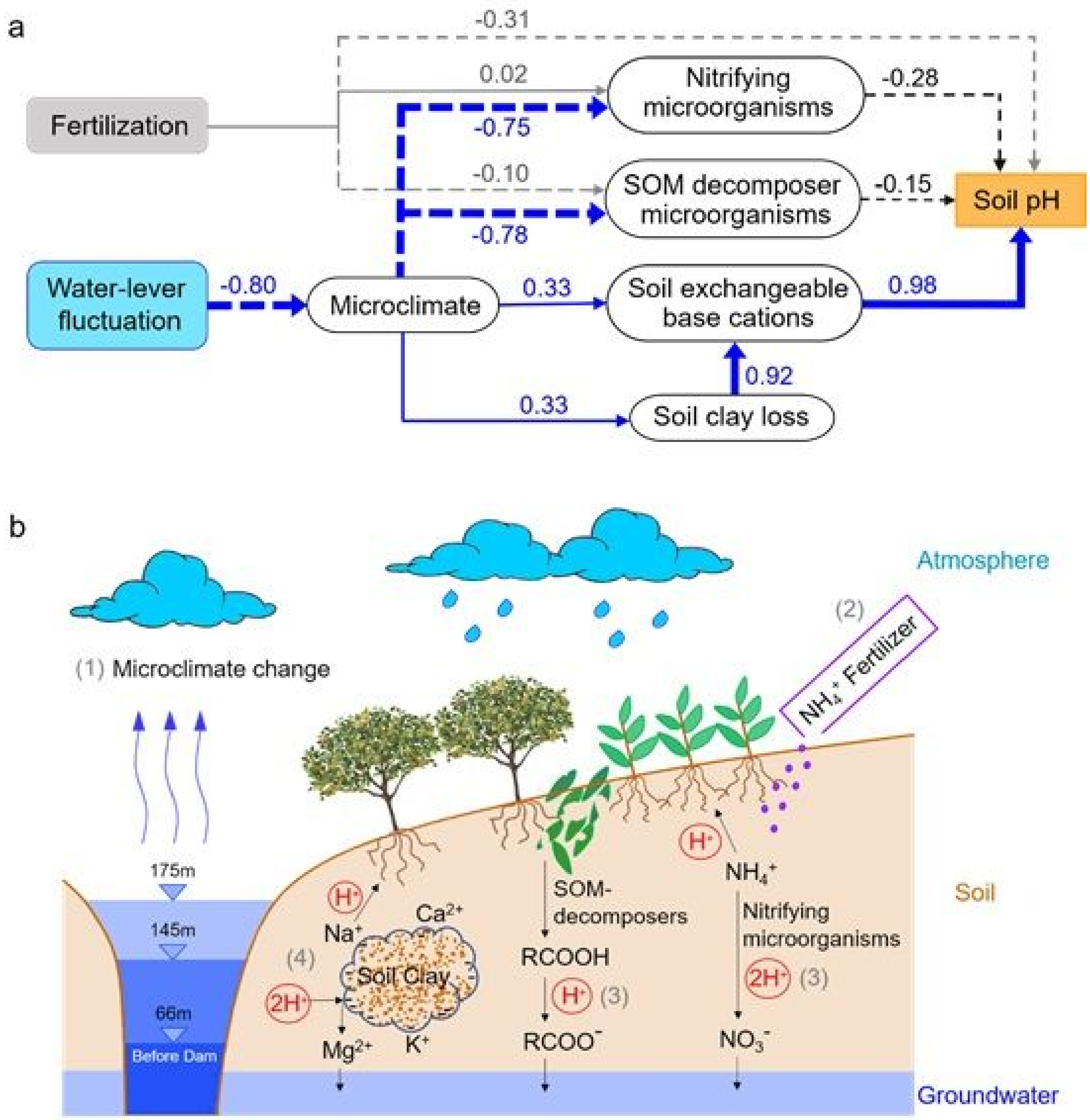

Figure 4

Schematic of the contributions to the decline in soil pH and corresponding mechanisms. (a) PLS-PM depicting the pathway of water-level change acting on soil pH in the experimental watershed affected by the TGD. Meteorological parameters include evaporation, relative humidity, soil temperature and precipitation; Nitrifying microorganisms include genera Nitrosomonadaceae, Nitrososphaeraceae and Nitrospiraceae; SOM-decomposer microorganisms (SOM decomposer microorganisms) include phylum Ascomycota, genus Bacillus, Streptomyces and Pseudomonas; Soil exchangeable base cations comprise Ca2+, Mg2+, Na+. The width of the arrows indicates the strength of the direct effect, and the wider the arrow, the greater the coefficient. Solid lines indicate positive effects and dashed lines indicate negative effects. (b) The main processes leading to soil acidification in the TGRA.

Supplementary Files

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